REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* July 2014

2. REPORT TYPE Final

3. DATES COVERED *(From - To)* 1-Oct-2012 - 31-Dec-2012

4. TITLE AND SUBTITLE
Assessment of Linear Seakeeping Performance Prediction of the R/V Melville

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER 0603236N

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER 100000539505/0040

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8. PERFORMING ORGANIZATION REPORT NUMBER
NSWCCD-80-TR-2014/021

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
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10. SPONSOR/MONITOR'S ACRONYM(S) ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
For the ONR Environment and Ship Motions Forecasting (ESMF) Future Naval Capabilities (FNC) Program, an understanding of the accuracy of linear ship motions prediction methods is of interest. An experiment was performed in the Maneuvering and Seakeeping (MASK) basin at the Naval Surface Warfare Center, Carderock Division (NSWCCD) to measure model-scale ship motion and waves, at moderate speeds, of the R/V Melville. Comparisons were then made between the model experiment results and linear, frequency-domain predictions using the USN Standard Motions Program (SMP95). This report details the comparison between these results and discusses differences observed and provides an assessment of the limitations of linear, frequency-domain prediction methods for the environmental conditions of interest to the ESMF FNC program.

15. SUBJECT TERMS
Ship Motions, Seakeeping, Frequency-Domain Predictions, SMP

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NO. OF PAGES	19a. RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE		29+vi	Christine Schleicher
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED			19b. TELEPHONE NUMBER (757)462-4374

20140903 448

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From: Commander, Naval Surface Warfare Center, Carderock Division
To: Office of Naval Research (ONR 331)

Subj: FORWARDING OF REPORT

Encl: (1) NSWCCD-80-TR-2014/021, "Assessment of Linear Seakeeping Performance Prediction of the R/V Melville" by Christine C. Schleicher, Christopher C. Bassler, Timothy C. Smith and Lauren W. Hanyok, July 2014
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NSWCCD-80-TR–2014/021 July 2014
Hydromechanics Department Report

Assessment of Linear Seakeeping Performance Prediction of the R/V Melville

By
Christine C. Schleicher
Christopher C. Bassler
Timothy C. Smith
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NSWCCD-50-TR–2014/021 ASSESSMENT OF LINEAR SEAKEEPING PERFORMANCE PREDICTION OF THE R/V MELVILLE

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INTERNATIONAL SYSTEM OF UNITS (SI) CONVERSION LIST

U.S. CUSTOMARY	METRIC EQUIVALENT
1 inch (in)	25.4 millimeter (mm), 0.0254 meter (m)
1 foot (ft)	0.3048 meter (m)
1 pound-mass (lbm)	0.4536 kilograms (kg)
1 pound-force (lbf)	4.448 Newtons (N)
1 foot-pound-force (ft-lbf)	1.3558 Newton-meters (N-m)
1 foot per second (ft/s)	0.3048 meter per second (m/s)
1 knot (kt)	1.6878 feet per second (ft/s) 0.5144 meter per second (m/s)
1 horsepower (hp)	0.7457 kilowatts (kW)
1 long ton (LT)	1.016 tonnes 1.016 metric tons 1016 kilograms (kg) 2240 pounds
1 inch water (60F)	248.8 Pascals (Pa)

ABSTRACT

For the ONR Environmental and Ship Motions Forecasting (ESMF) Future Naval Capabilities (FNC) Program, an understanding of the accuracy of linear ship motions prediction methods is of interest. An experiment was performed in the Maneuvering and Seakeeping (MASK) basin at the Naval Surface Warfare Center Carderock Division (NSWCCD) to measure model-scale ship motion and waves, at moderate speed, of the R/V Melville. Comparisons were then made between the experimental results and linear, frequency-domain predictions using the USN Standard Motions Program (SMP95). This report details the comparison of the results, discusses differences observed, and provides an assessment of the limitations of linear, frequency-domain prediction methods for the environmental conditions of interest to the ESMF FNC program.

ADMINISTRATIVE INFORMATION

The work described in this report was performed by the Naval Architecture & Engineering Department at the Naval Surface Warfare Center, Carderock Division (NSWCCD). The work was funded by the Office of Naval Research, Code 331, as part of the Environmental and Ship Motions Forecasting (ESMF) Future Naval Capabilities (FNC) Program (Program Element 0602123N), under the direction of Dr. Paul Hess (Program Element 0602236N).

INTRODUCTION

The Office of Naval Research's (ONR) Environmental and Ship Motion Forecasting (ESMF) Future Naval Capability (FNC) Program is developing technologies to support Sea Basing initiatives. Some of the technologies will provide environmental and ship motion forecasting, enabling predictions of windows of opportunity for seabasing operations such as inter/intraship material, personnel, and vehicle movement; skin-to-skin operations; wet-deck operations; and, launch and recovery of manned and unmanned vehicles.

To support ESMF, ONR is using full-scale measurements from the R/V Melville to investigate Science and Technology (S&T) developments that may enable and improve real-time prediction of ship motions. The R/V Melville (T-AGOR 14) (Figure 1) is a research vessel operated by Scripps Institute of Oceanography (SIO). This 85m, 3000 tonne (279ft, 2955 LT) vessel has been in service for more than four decades as an ocean-going science platform. This platform will be used at the end of Phase IB of the ESMF FNC program to demonstrate and evaluate ESMF systems currently under development.

Understanding the assumptions and limitations of various ship motion modeling approaches is critical for ESMF. In order to provide a baseline for interpretation of ESMF data obtained during the full-scale demonstration aboard the R/V Melville, two parallel paths were taken to generate motion data for this vessel. First, model-scale experiments in regular and irregular waves were conducted and the motions of the R/V Melville at 1/23rd scale were recorded [1]. Second, motions of the R/V Melville in irregular seas were predicted using the USN Standard Ship Motion Program (SMP95), a linear, frequency-domain seakeeping prediction [2]. This report documents the R/V Melville motions data obtained from both paths, and is intended to be used as a reference during the full scale ESMF demonstration. The data provided herein highlights conditions in which the motions predicted by SMP95 align well with model test data, and also indicates conditions where the two data sets do not align well. The conditions in which SMP95 data and model test data do not align well should be observed carefully during the full-scale demonstration. One additional note regarding this report is that it is not intended to be used as a verification and/or validation assessment for SMP95. While comparisons are made between experimental data and SMP95 output, there is simply not enough data provided herein to substantiate any verification/validation conclusions regarding SMP95.

Figure 1. Photograph of the R/V Melville.

MOTIONS DATA GENERATED THROUGH MODEL TESTING

A model test was performed in the Maneuvering and Seakeeping (MASK) basin at the Naval Surface Warfare Center Carderock Division (NSWCCD) for the R/V Melville. The 1/23rd scale model of the R/V Melville constructed for this test included the skeg, bilge keels, and close approximation of propulsion pods. The model was operated as a free-running model, and data was collected for head seas, bow seas, beam seas, quartering seas, and following seas. Time-synchronized model ship motion and wave measurement data was collected for full-scale speeds of 0, 8, and 12 knots, in both regular and irregular uni-directional wave conditions representing Sea States 3, 4, and 5. Characteristics of the three Sea States, generated as a Bretschneider spectrum in the MASK, are provided in Table 1.

Table 1: Sea State Properties

Sea State	Significant Wave Height, meters	Most Probable Period, seconds
Sea State 3	0.9	7.5
Sea State 4	1.9	8.8
Sea State 5	3.2	9.7

Figure 2 shows an average measured versus target sea spectrum for the Sea State 3 condition. Due to the method of wave generation in the MASK, the measured sea spectrum does not exactly match the target Bretschneider sea spectrum over the range of frequencies. The measured sea spectrum has more energy than the target at lower frequencies, and less energy at the higher frequencies. This energy disparity should be considered when comparing the experimental motion measurements that result from the achieved Sea State to the SMP predictions that use the target Bretschneider spectrum.

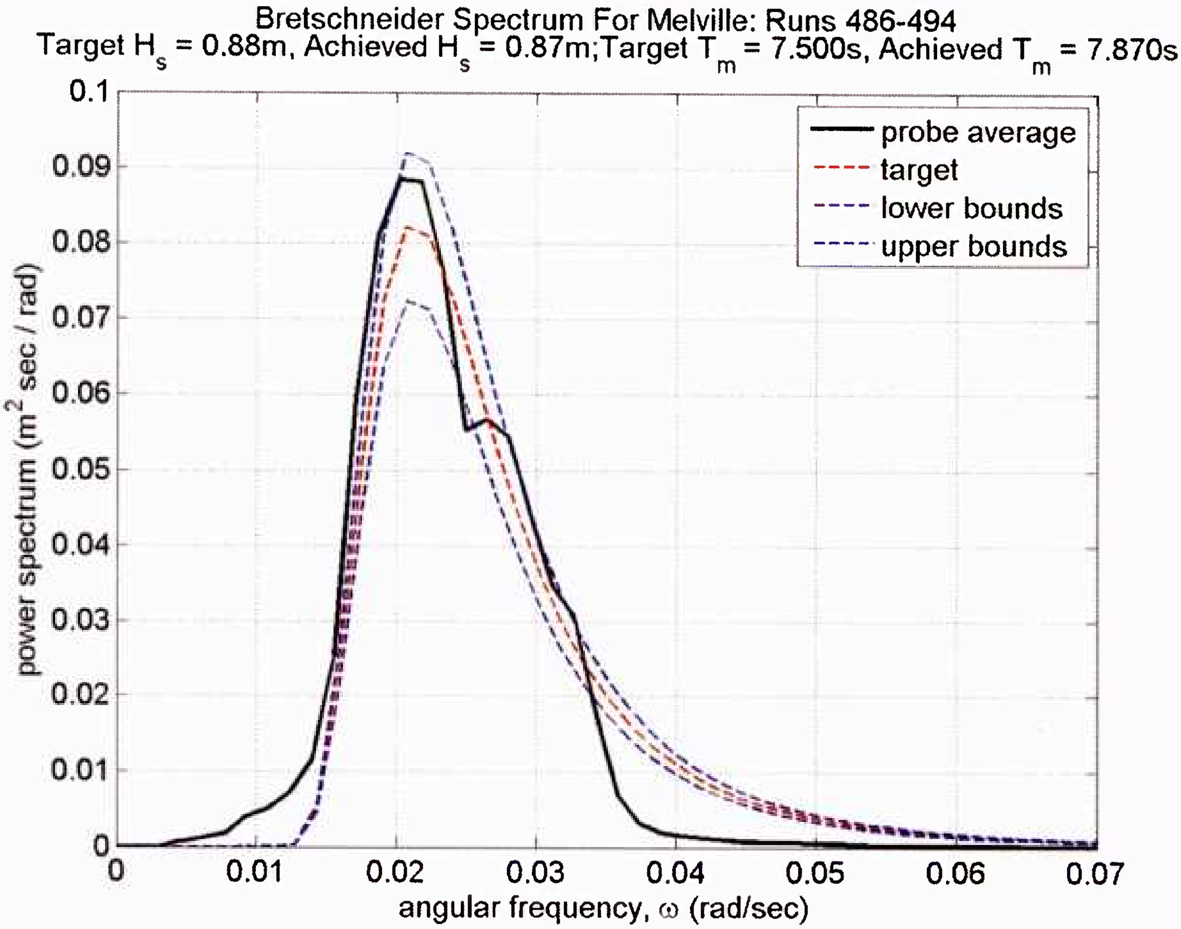

Figure 2. Sea spectrum achieved versus target spectrum for Sea State 3.

The response amplitude operators (RAOs) were calculated based on the ship's pitch and heave in both regular and irregular seas. Individual runs were concatenated into a single longer record prior to analysis. For the regular seas, Fourier analysis was first performed on the roll, pitch, and carriage wave height sensor data. The RAOs were then calculated as the ratio of the first harmonic Fourier coefficient of motion to the first harmonic Fourier coefficient of the wave height. The wave height data used for analysis was dependent on the relative wave heading of the condition. The west carriage wave height sensor was used for head seas and the north sensor was used for beam and following seas because these were verified to be outside of the radiated waves of the model.

For the irregular seas, spectral analysis was first performed on the roll, pitch, and carriage wave height data to compute the spectral densities of each signal. The ratio of motion to wave data was then calculated by dividing the spectral density of the desired motion by the spectral density of the wave data. The RAO for each encounter frequency is equal to the square root of the spectral density ratios. The wave height data used for analysis was again dependent of the relative wave heading of the condition. The west carriage wave height sensor was used for head and bow seas, the north sensor was used for beam and following seas, and the south sensor was used for quartering seas.

LINEAR SHIP MOTION PREDICTIONS USING SMP95

The USN Standard Ship Motion Program (SMP95) is a linear, frequency-domain ship motions numerical simulation tool. SMP95 enables predictions of motions (displacements, velocities, and accelerations) for a ship advancing at constant speed, with arbitrary heading, in irregular seas [2]. Irregular seas are modeled in SMP95 using a two-parameter Bretschneider wave spectral model. RAO predictions are output for irregular seas.

SMP95 provides a potential flow solution based on linearized strip theory. The assumptions inherent in this theory are that ship length is large compared to beam and draft, and that hull section and waterplane properties are represented by the calm water values. The latter condition requires that ship motions be limited to small amplitudes. Additionally, in pure head seas and pure following seas, SMP95 predicts zero roll, sway and yaw.

Long-crested waves were used in the SMP95 simulations for comparisons with the seakeeping model experiments of the R/V Melville in the NSWCCD Maneuvering and Seakeeping (MASK) Basin [1]. The R/V Melville hull geometry utilized for the SMP95 predictions included the hull itself, plus bilge keels and skeg. The propulsion pods were not modeled. The R/V Melville was modeled in SMP95 to match the as-tested displacement, trim, and metacentric height (GM) with free surface correction from reference [1].

To facilitate the comparison of RAOs from the model test with the RAOs predicted by SMP95, a slight modification to the SMP95 prediction results was made. RAOs generated from model test data were reported in units of degrees per meter, whereas RAOs generated using SMP95 were calculated in units of that quantity, degrees per meter, squared. Upon researching this discrepancy further, it was determined that the difference lies in a definition of RAO which has changed over time. The Response Amplitude Operator was originally defined as the square of the ratio of the scalar amplitude of response and the exciting wave amplitude [3]. However, in more recent years, the unsquared ratio has been used as the definition of RAO. In the current situation, RAOs derived from model test data were calculated using the unsquared ratio and the RAOs calculated by SMP95 were output as the squared ratio. Therefore, the square root of each RAO computed by SMP95 was calculated, and this result was compared with the corresponding RAO derived from the model test data.

COMPARISONS BETWEEN SIMULATIONS AND EXPERIMENTS

Overview of Conditions for Comparison

RAO's from SMP95 was compared to those derived from model scale experimental data. RAOs for irregular waves provide important information for the upcoming ESMF demonstration. However, RAO data generated from model-scale testing in 1/60th slope regular waves are also included in this comparison because this model test condition is the best representation of the linear motion assumptions inherent in the SMP95 calculations. The regular wave conditions are specified in Table 2.

Table 2. Regular Wave Conditions for Comparison (Full-Scale) Between SMP95 and Experimental Results of the R/V Melville

Speed [knots]	Wave Slope --	Frequency [Hz]	Encounter Frequency [Hz]	Heading --
8	1/60	0.20	0.306	Head
8	1/60	0.14	0.195	Head
8	1/60	0.12	0.151	Head
8	1/60	0.10	0.127	Head
8	1/60	0.09	0.110	Head
12	1/60	0.20	0.358	Head
12	1/60	0.14	0.219	Head
12	1/60	0.12	0.168	Head
12	1/60	0.10	0.141	Head
12	1/60	0.09	0.122	Head
8	1/60	0.20	0.200	Beam
8	1/60	0.14	0.138	Beam
8	1/60	0.12	0.116	Beam
8	1/60	0.10	0.100	Beam
8	1/60	0.09	0.089	Beam
12	1/60	0.20	0.199	Beam
12	1/60	0.14	0.143	Beam
12	1/60	0.12	0.118	Beam
12	1/60	0.10	0.099	Beam
12	1/60	0.09	0.089	Beam
8	1/60	0.20	0.095	Following
8	1/60	0.14	0.090	Following
8	1/60	0.12	0.079	Following
8	1/60	0.10	0.074	Following
8	1/60	0.09	0.068	Following
12	1/60	0.20	0.084	Following
12	1/60	0.14	0.063	Following
12	1/60	0.12	0.063	Following
12	1/60	0.10	0.061	Following
12	1/60	0.09	0.058	Following

Comparisons are shown between the measured and predicted RAOs for roll and pitch, and for head, beam, and following seas at full-scale equivalent speeds of 8 and 12 knots. Predicted and measured RAOs for each speed and motion are plotted as a function of wave encounter frequency for each wave heading. All RAO values are in units of degrees per meter and provided for multiple wave encounter frequencies.

In ideal conditions, a vessel would experience no roll in pure head or following seas, as is the case for the linear SMP model with long-crested wave conditions. However, the model in the experiment was manually piloted, resulting in small deviations from pure head or following seas, and therefore experienced roll in head and following seas.

Comparisons of Roll RAOs

Figures 3-8 show roll RAOs plotted as a function of wave encounter frequency for Sea State 3, at 8 knots, and 12 knots, and in following, beam, and head seas. Figures 15-20 show results for the same conditions for Sea State 4, and Figures 27-32 show the results at SS5. SMP predicts zero roll for pure head and following seas under all conditions, as expected. However, in beam seas, there is reasonable correlation between predicted and measured RAO values. The RAO peak is likely shifted because GM was matched between the physical model and full-scale ship (roll periods were not specifically matched). The peak for SMP is at a lower frequency than the physical model results for all cases. In general, the agreement between the data and SMP predictions improves with an increase in Sea State.

Following Sea

Examination of the roll RAOs derived from model test data for Sea States 3, 4, and 5 (Figures 3, 4, 15, 16, 27, and 28) indicates that the shape of the curve at 8 knots is similar for the three environmental conditions. The results show a significant increase in RAO from Sea State 3 to Sea State 4, and a subsequent significant decrease in RAO from Sea State 4 to Sea State 5. In fact, the maximum RAO for Sea State 5 is lower than that derived for Sea State 3.

RAO curves for 12 knots appear to be more consistent. For all three Sea States at $1/60^{th}$ slope regular waves, the minimum RAO values occur at an encounter frequency of roughly 0.4 rad/sec. Maximum values vary somewhat, both in amplitude and in the encounter frequency at which that value occurs. However, values derived for Sea State 3 and Sea State 5 are similar, but values for Sea State 4 are markedly different.

The roll RAO values for following seas warrant further examination.

Beam Sea

In all three Sea States (Figures 5, 6, 17, 18, 29, and 30) the roll RAO values predicted by SMP for 8 knots are nearly identical to those predicted for 12 knots throughout the encounter frequency range. Similarly, the roll RAO values derived from model test data at 8 knots resemble those derived for 12 knots throughout the encounter frequency range. Variation of the maximum RAO value (between the SMP prediction and the model test data) is greatest for Sea State 3, and is small for Sea States 4 and 5.

Head Sea

An analysis of RAOs derived from model test data in Sea States 3, 4, and 5 (Figures 7, 8, 19, 20, 31, and 32) reveals that the data follows a similar pattern in all three Sea States, and for both 8 and 12 knots. RAO amplitudes are also similar throughout the encounter frequency range, with the exception of higher RAO amplitudes occurring at 12 knots in Sea State 3 in the encounter frequency range of 0.5 – 0.6 rad/sec.

Comparisons of Pitch RAOs

As a general note, SMP prediction of pitch RAO is independent of Sea State. Thus the pitch RAOs predicted in Sea States 3, 4, and 5 for a given heading are identical.

Figures 9-14 show pitch RAOs plotted as a function of wave encounter frequency for Sea State 3, at 8 knots and 12 knots, and for following, beam, and head seas. Figures 21-26 show results for the same conditions for Sea State 4, and Figures 33-38 show the same conditions at Sea State 5. In general, the correlation between the data and SMP predictions is not good for following and beam seas, and is reasonably good for head seas across Sea State and speed ranges. For beam seas, SMP tends to under predict the RAOs, while for following seas, SMP tends to over predict the RAOs.

Following Sea

SMP predictions of pitch RAO in following seas do not correlate well with RAO values derived from model test data. In all three Sea States, there is a portion of the RAO curve for the 8 knot case in which the trend is similar for the predicted and experimentally derived data. However, no such similarity exists between the predicted and measured values for the 12 knot case.

Beam Sea

Pitch RAO predictions from SMP bear little resemblance to the RAO curves derived from the model test data for the beam sea condition. For 8 and 12 knots in all three Sea States, experimental data indicates a dip in the RAO curve at encounter frequencies ranging from 0.6-0.8 rad/sec. This data also features a peak in the RAO curve in the encounter frequency range of 1.2-1.4 rad/sec. In contrast, SMP predictions for 8 and 12 knots show RAO amplitudes that increase continually with encounter frequency, peaking at an encounter frequency in the vicinity of 1.3 rad/sec (8 knots case) and 1.4-1.6 rad/sec (12 knots case). Additionally, the RAO amplitudes derived from model test data are markedly different (and larger in magnitude) than those predicted by SMP.

Head Sea

There is good correlation in the overall trend of predicted and measured pitch RAO values for the head sea condition for both speeds and all three Sea States. However, the SMP predictions vary smoothly, and the model test data do not. The RAO amplitudes are very close in magnitude, and the encounter frequency at which the peak RAO occurs is also very close. There appears to be a smaller peak in the RAO values derived from the model data; the peak occurs in the encounter frequency range of 0.5-0.6 rad/sec.

CONCLUSIONS

A linear, frequency-domain ship motions numerical tool, SMP95, was used to predict RAO values for roll and pitch for head, beam, and following seas for the model scale R/V Melville, at 8 and 12 knots. The results obtained from SMP95 were compared to those obtained experimentally. Motion RAOs for both roll and pitch were plotted as a function of wave encounter frequency. Conditions included head, beam, and following seas, at 8 and 12 knots. For roll RAOs as a function of wave encounter frequency, beam seas correlated the best between predicted and measured RAO values. The best correlation for pitch motion was for the head seas condition. There are a few reasons that the differences between the data and predictions exist. One reason is that the Sea State used in the SMP runs is an ideal Bretschneider spectrum, while the achieved Sea State in the MASK is slightly different (see Figure 2). There is an obvious difference in wave energy at various frequencies, which will likely have an effect on the generated ship motions. Another reason is that SMP is a linear code, while the physical model motions are likely non-linear, especially at the higher Sea States. A further reason for the differences is that while the ship characteristics were matched between model and full-scale (i.e. GM), roll and pitch period were not specifically matched.

The comparisons between SMP95 predictions and model test data presented herein are not meant to be used as a verification/validation of SMP95. Rather, the data is intended to be used for reference during the ESMF demonstration. The RAOs predicted in SMP95 give an indication of responses anticipated if the motion of the R/V Melville is a linear function of the sea environment; the model test results give an indication of what the actual motions of the R/V Melville may be like in the same environment. These two data sets provide background information for assessing the RAO values determined in near real-time during the full scale ESMF demonstration aboard the R/V Melville in late summer 2013.

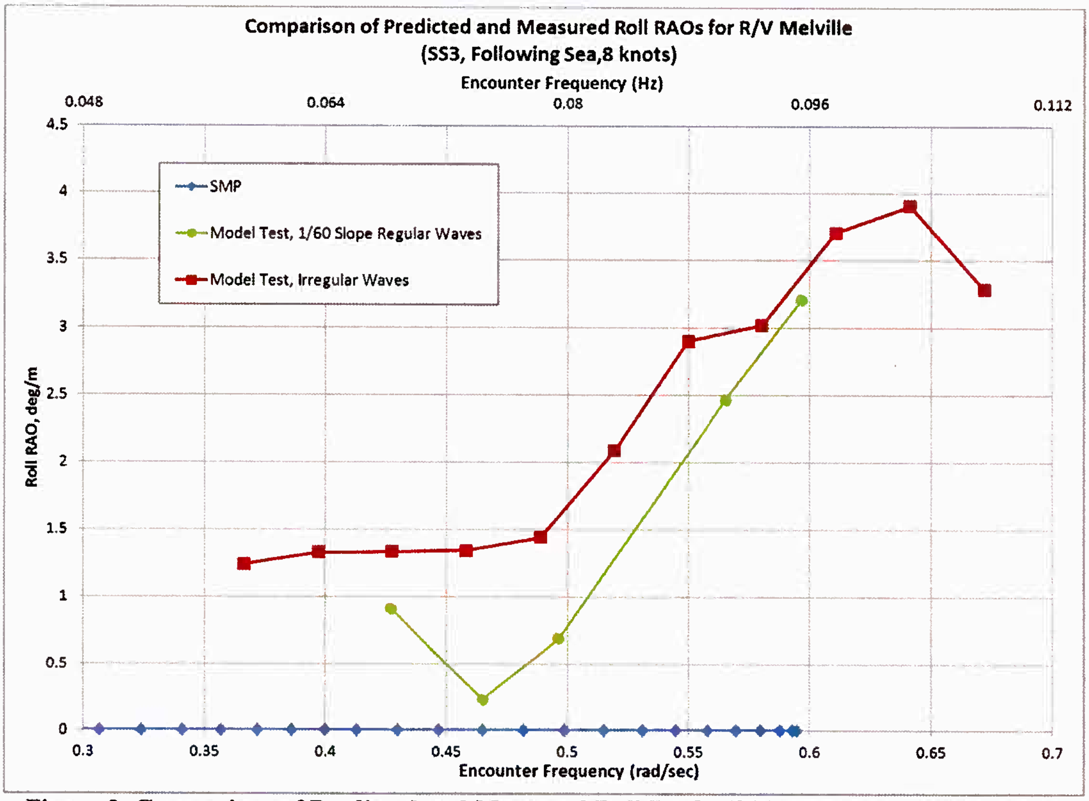

Figure 3. Comparison of Predicted and Measured Roll RAOs (SS3, Following Seas, 8 knots)

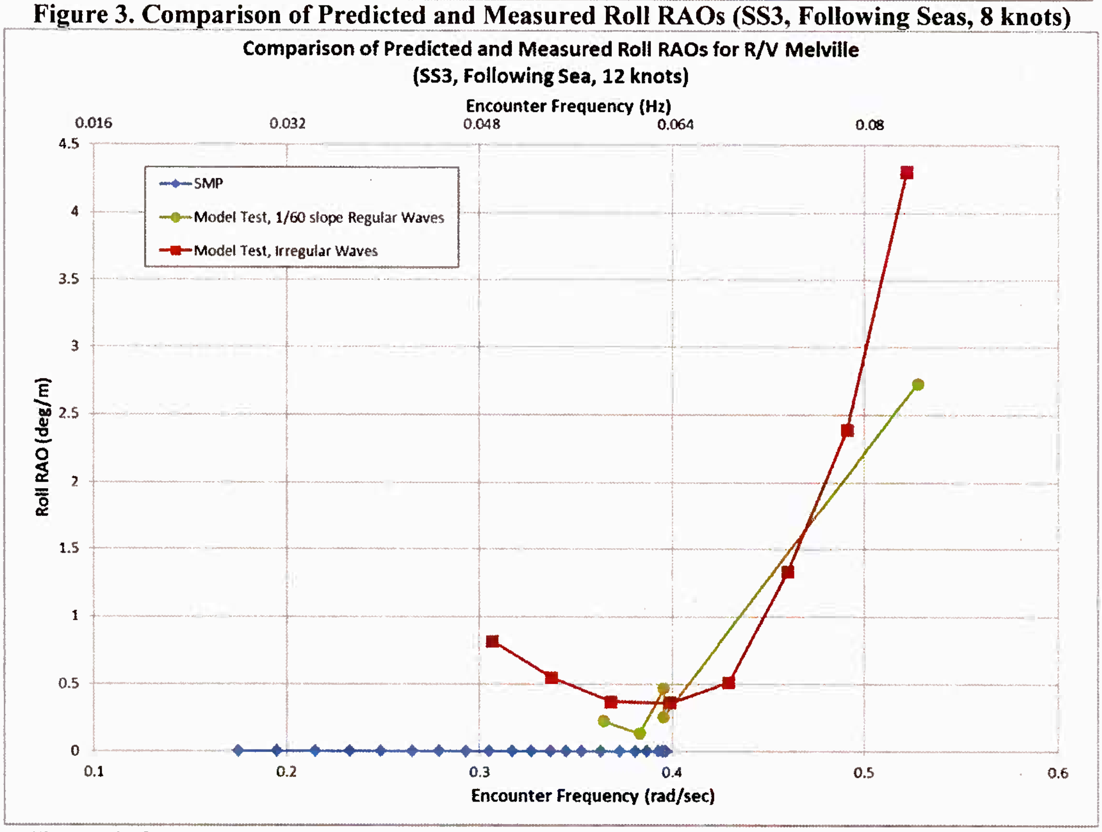

Figure 4. Comparison of Predicted and Measured Roll RAOs (SS3, Following Seas, 12 knots)

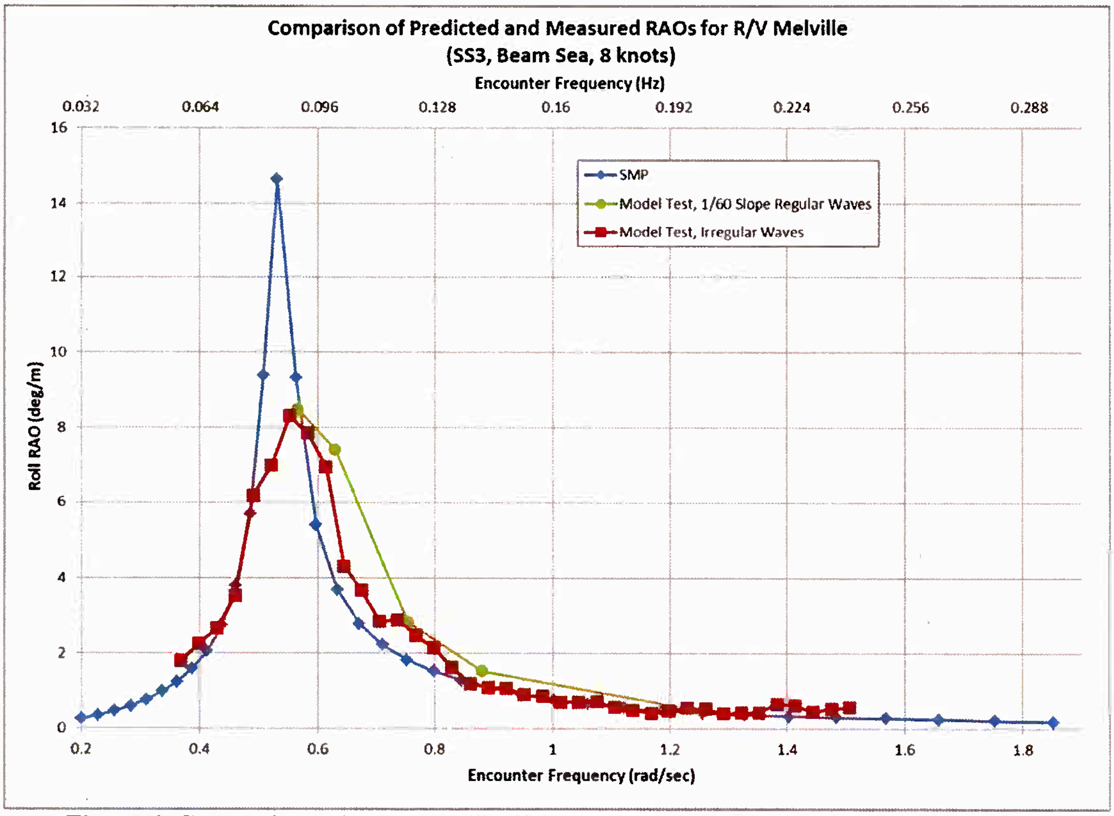

Figure 5. Comparison of Predicted and Measured Roll RAOs (SS3, Beam Sea, 8 knots)

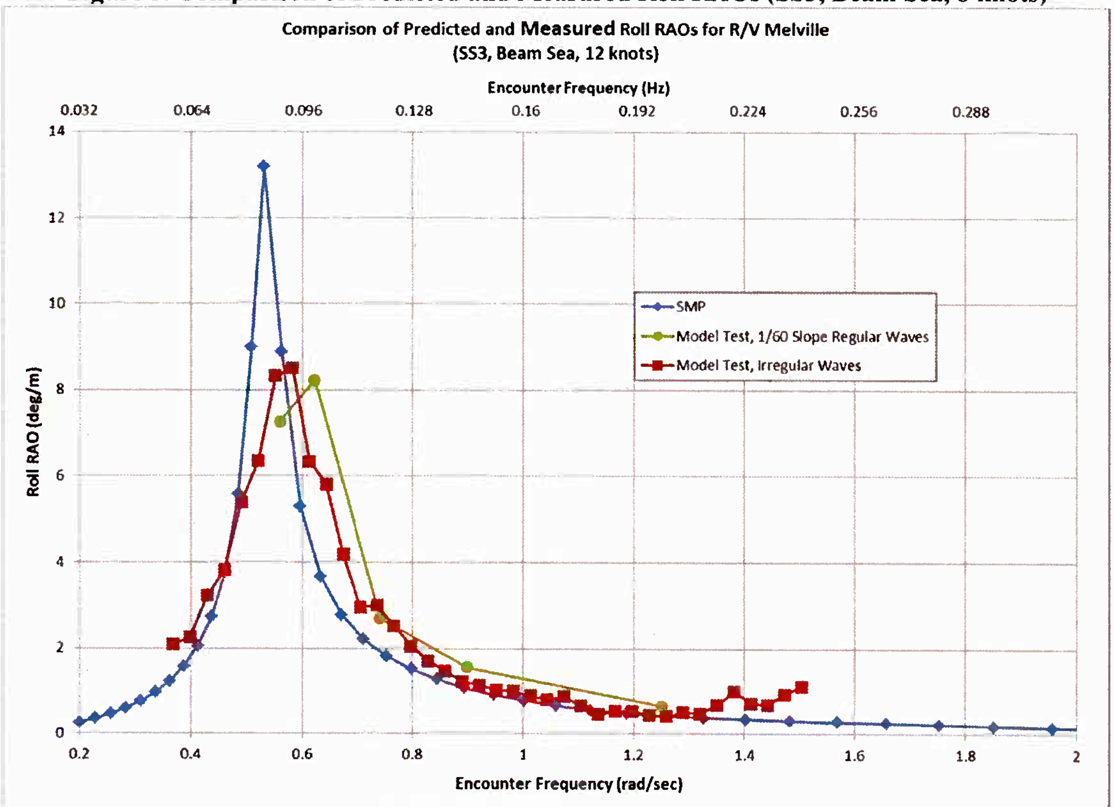

Figure 6. Comparison of Predicted and Measured Roll RAOs (SS3, Beam Sea, 12 knots)

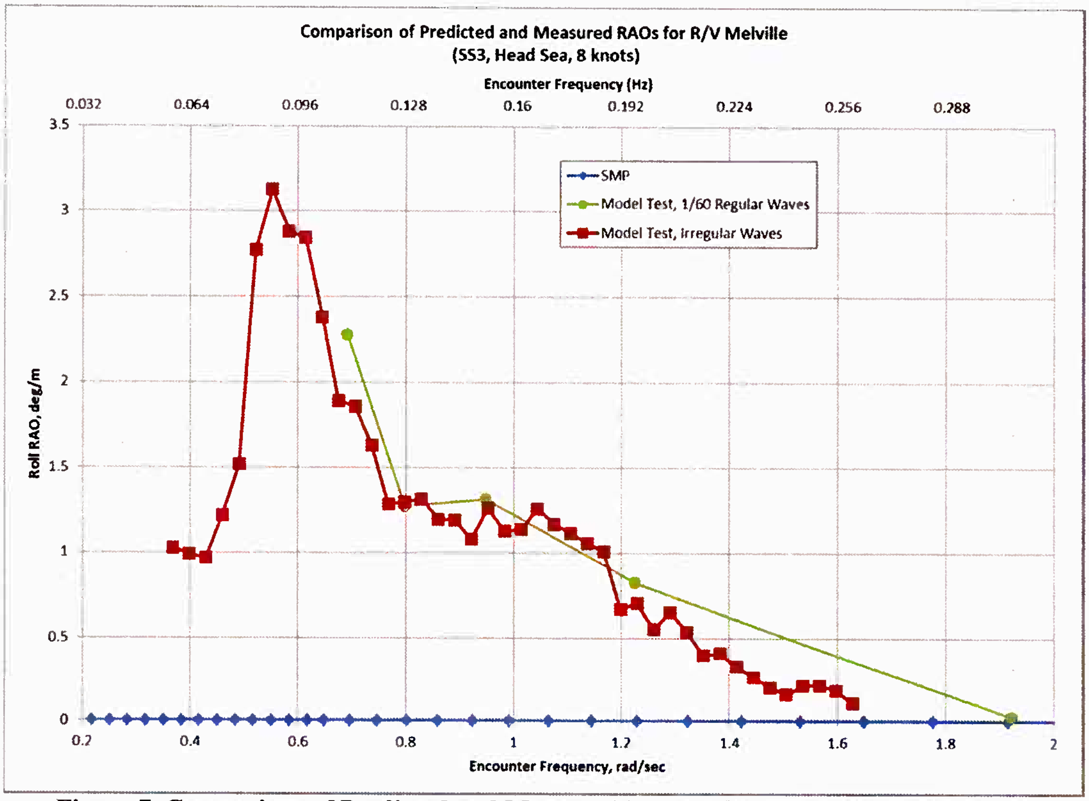

Figure 7. Comparison of Predicted and Measured Roll RAOs (SS3, Head Sea, 8 knots)

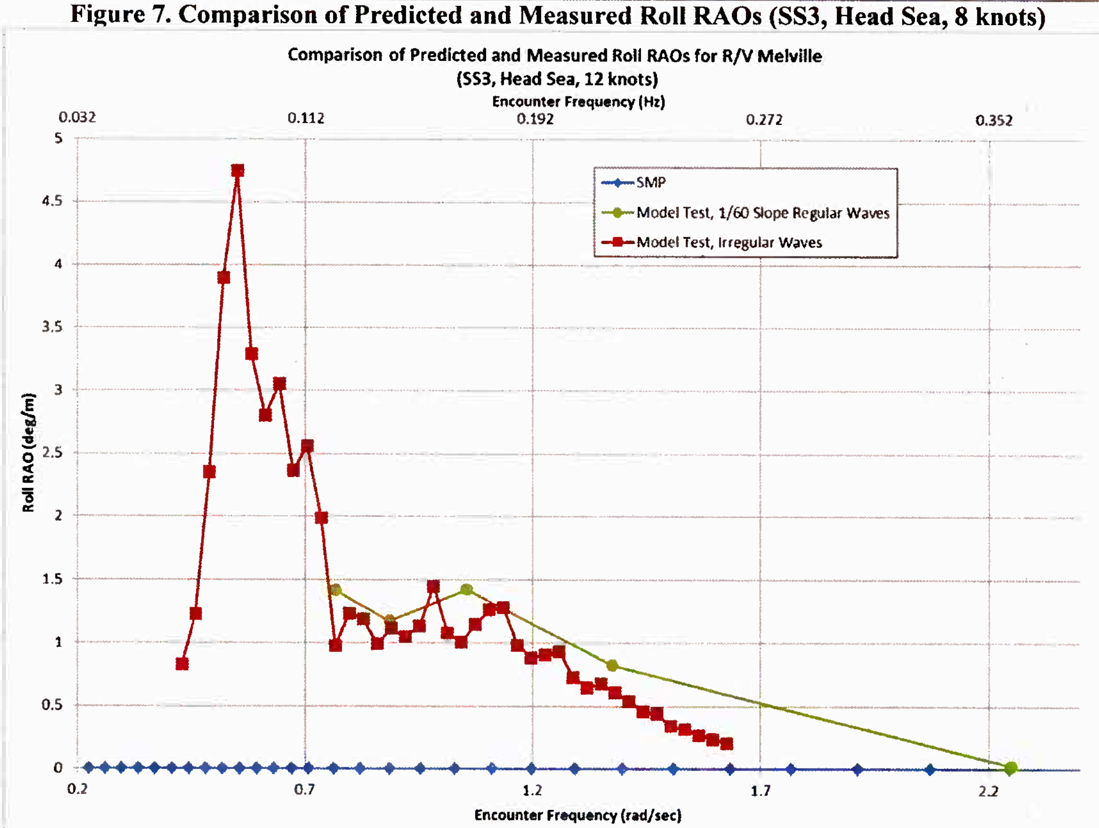

Figure 8. Comparison of Predicted and Measured Roll RAOs (SS3, Head Sea, 12 knots)

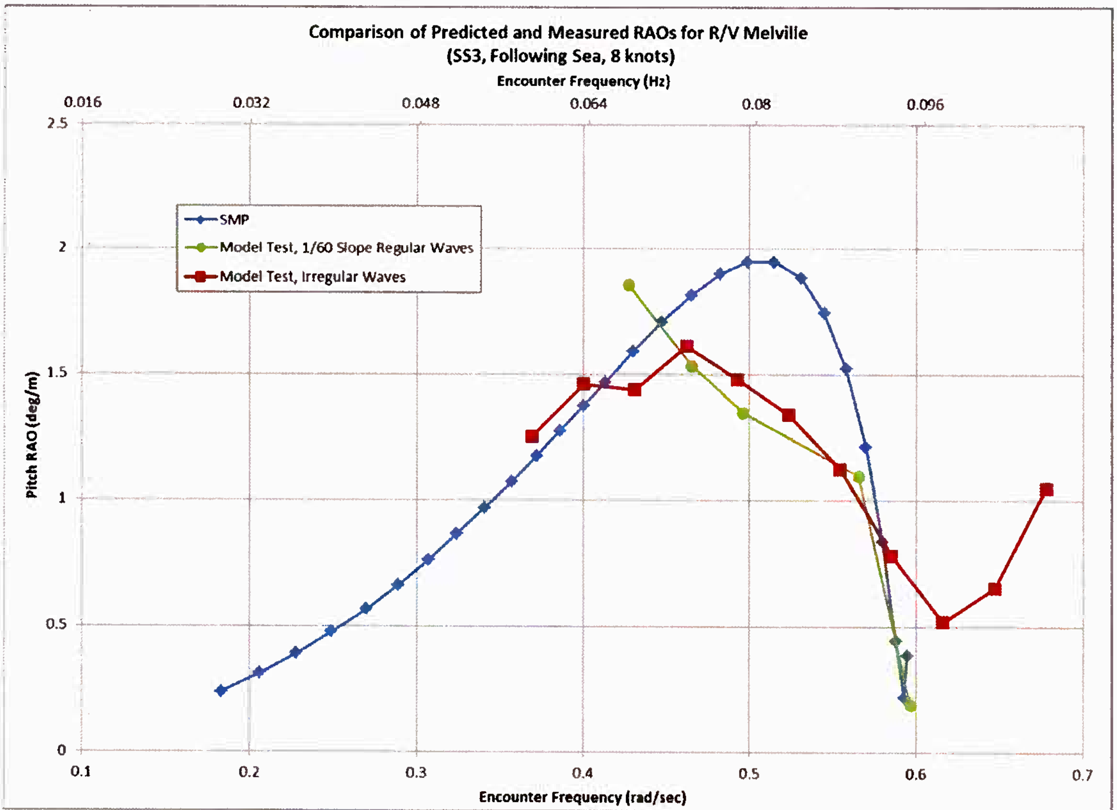

Figure 9. Comparison of Predicted and Measured Pitch RAOs (SS3, Following Sea, 8 knots)

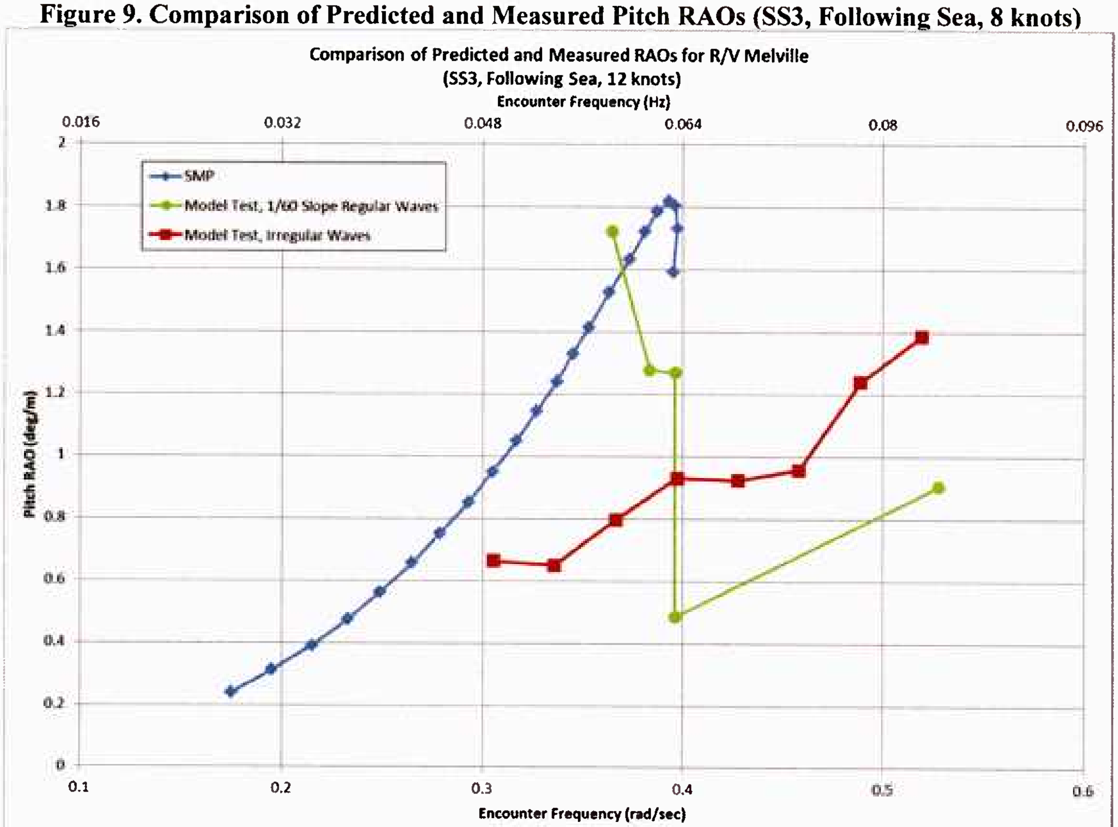

Figure 10. Comparison of Predicted and Measured Pitch RAOs (SS3, Following Sea, 12 knots)

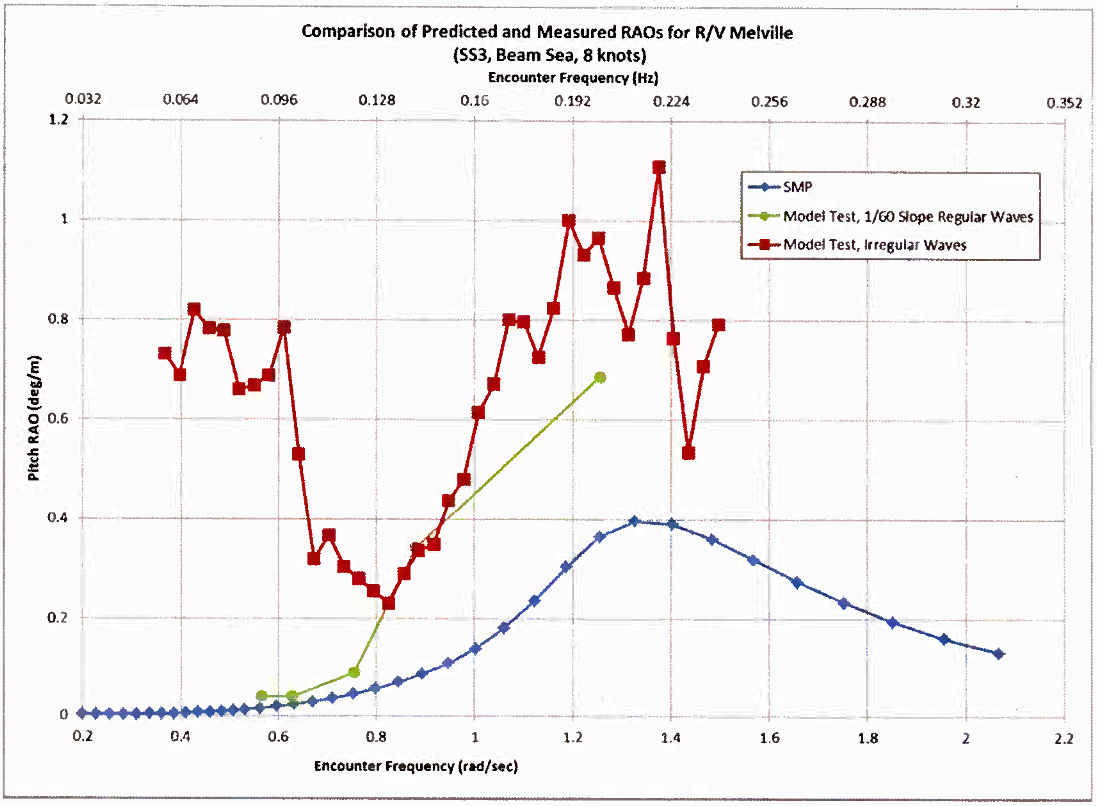

Figure 11. Comparison of Predicted and Measured Pitch RAOs (SS3, Beam Sea, 8 knots)

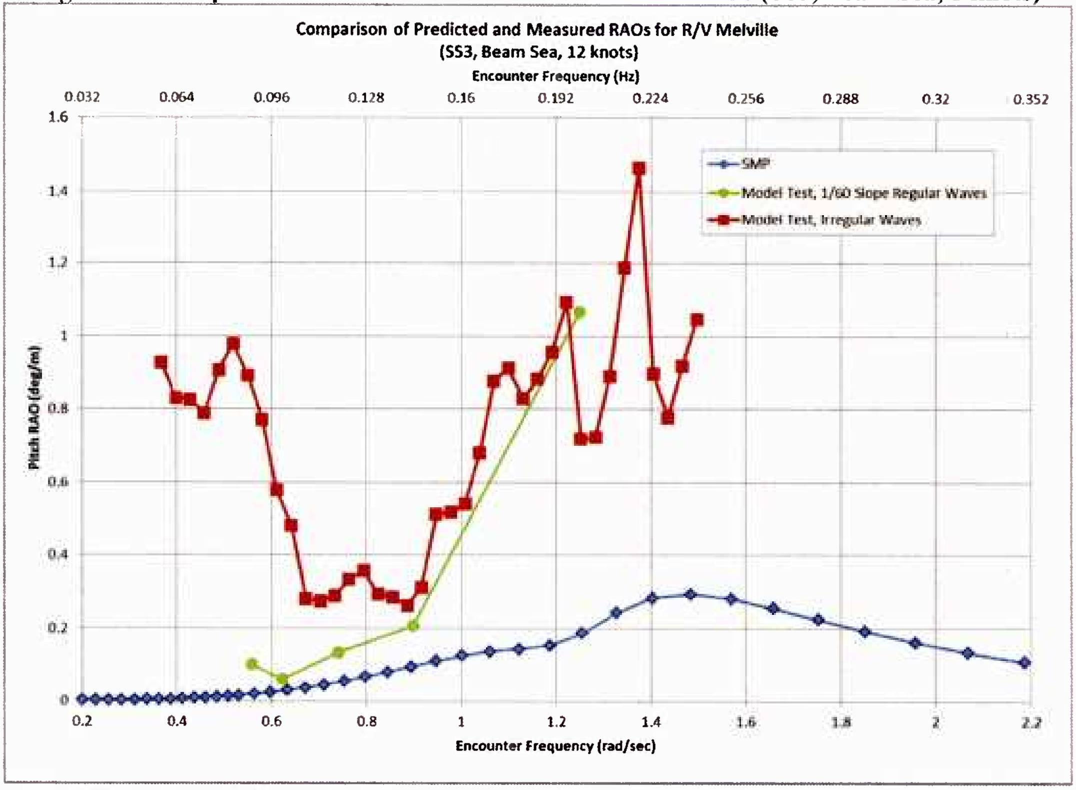

Figure 12. Comparison of Predicted and Measured Pitch RAOs (SS3, Beam Sea, 12 knots)

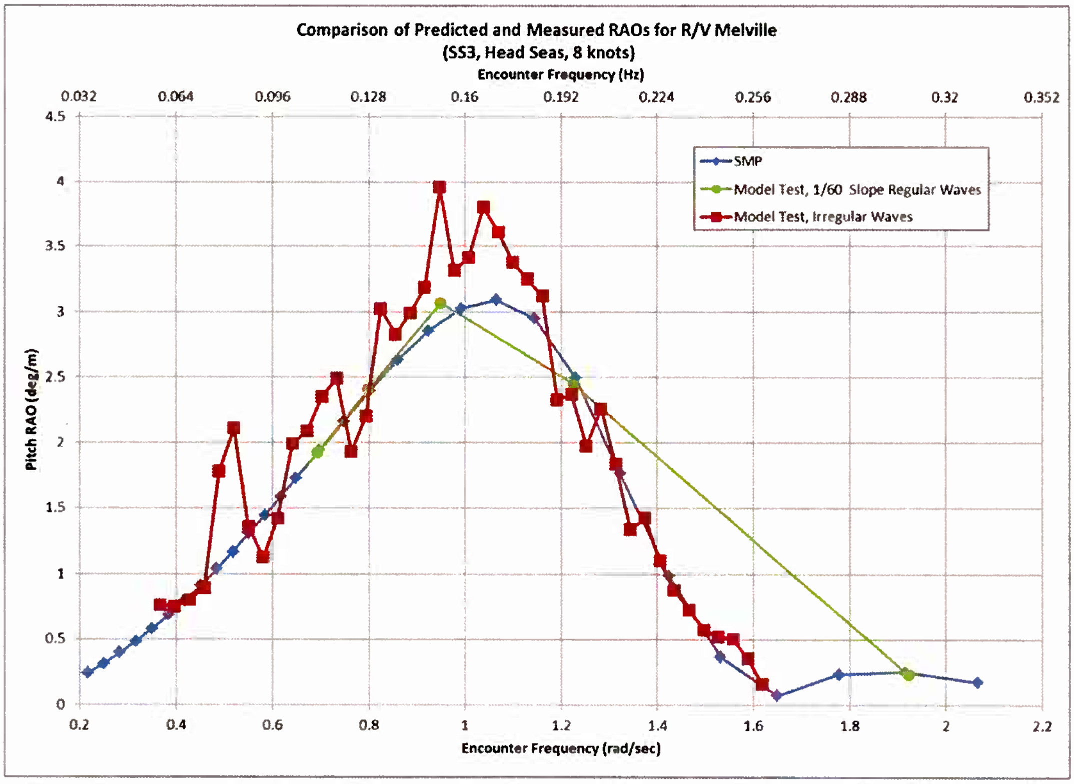

Figure 13. Comparison of Predicted and Measured Pitch RAOs (SS3, Head Seas, 8 knots)

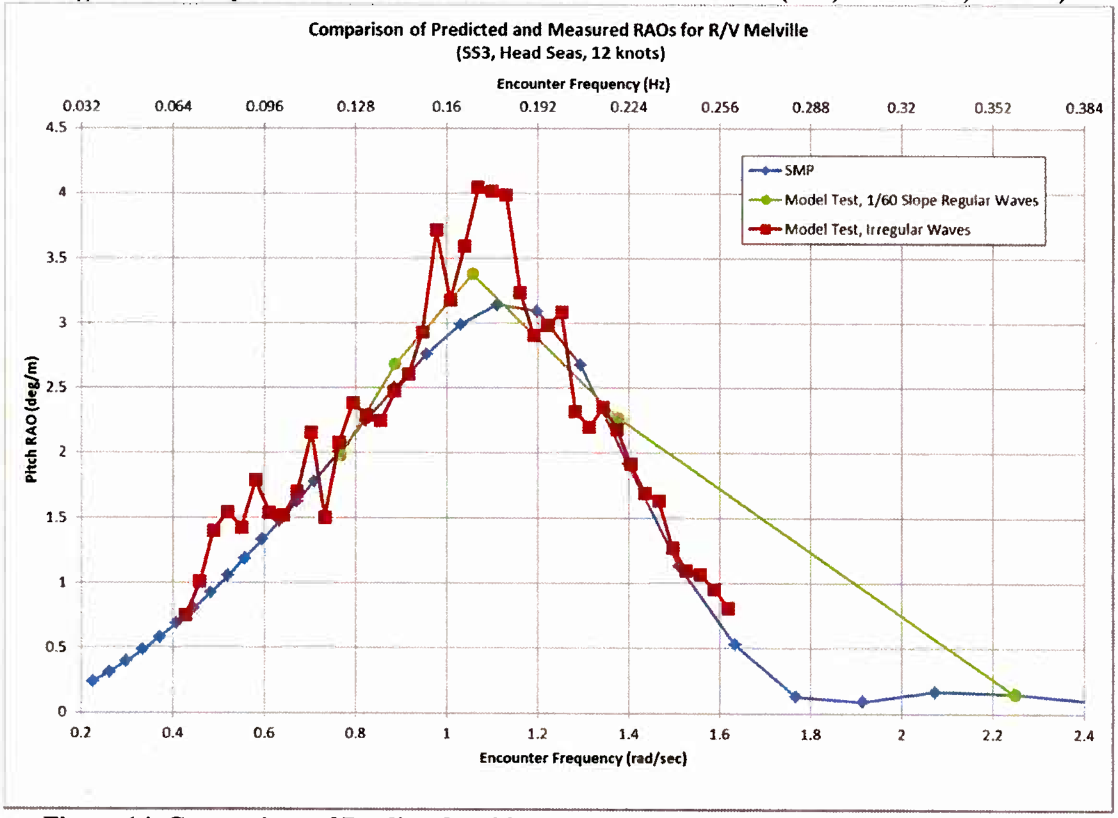

Figure 14. Comparison of Predicted and Measured Pitch RAOs (SS3, Head Seas, 12 Knots)

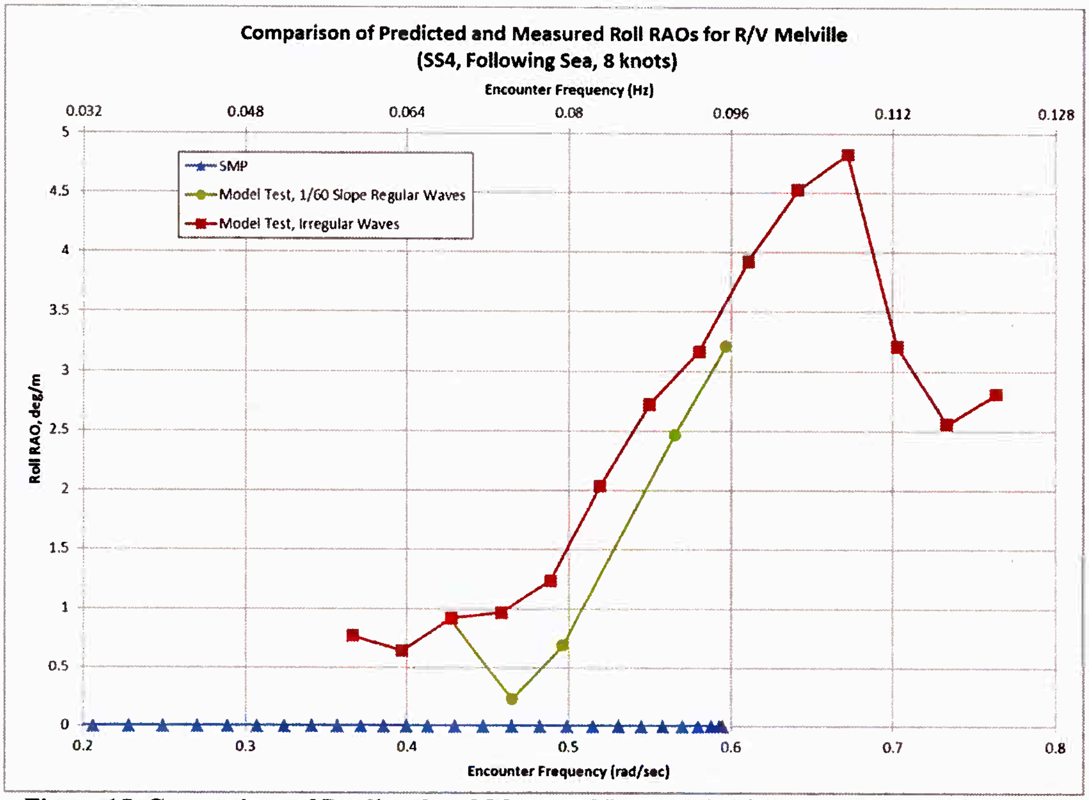

Figure 15. Comparison of Predicted and Measured Roll RAOs (SS4, Following Sea, 8 knots)

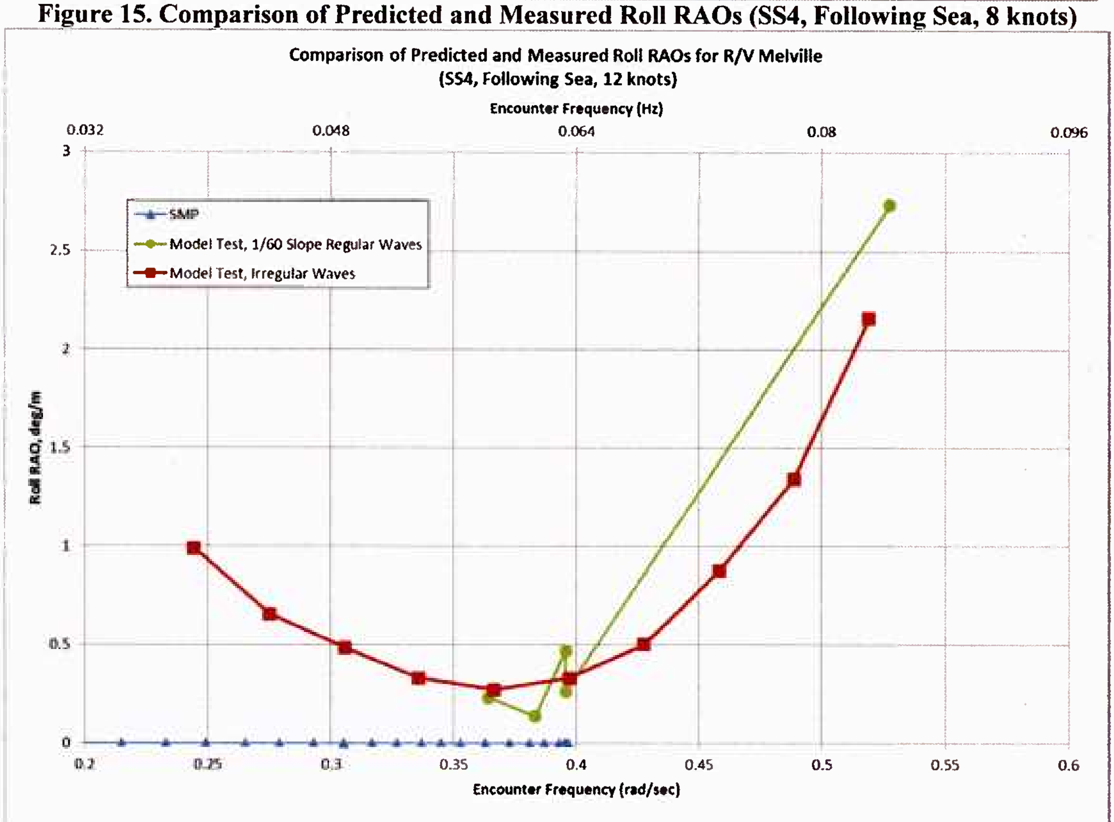

Figure 16. Comparison of Predicted and Measured Roll RAOs (SS4, Following Sea, 12 knots)

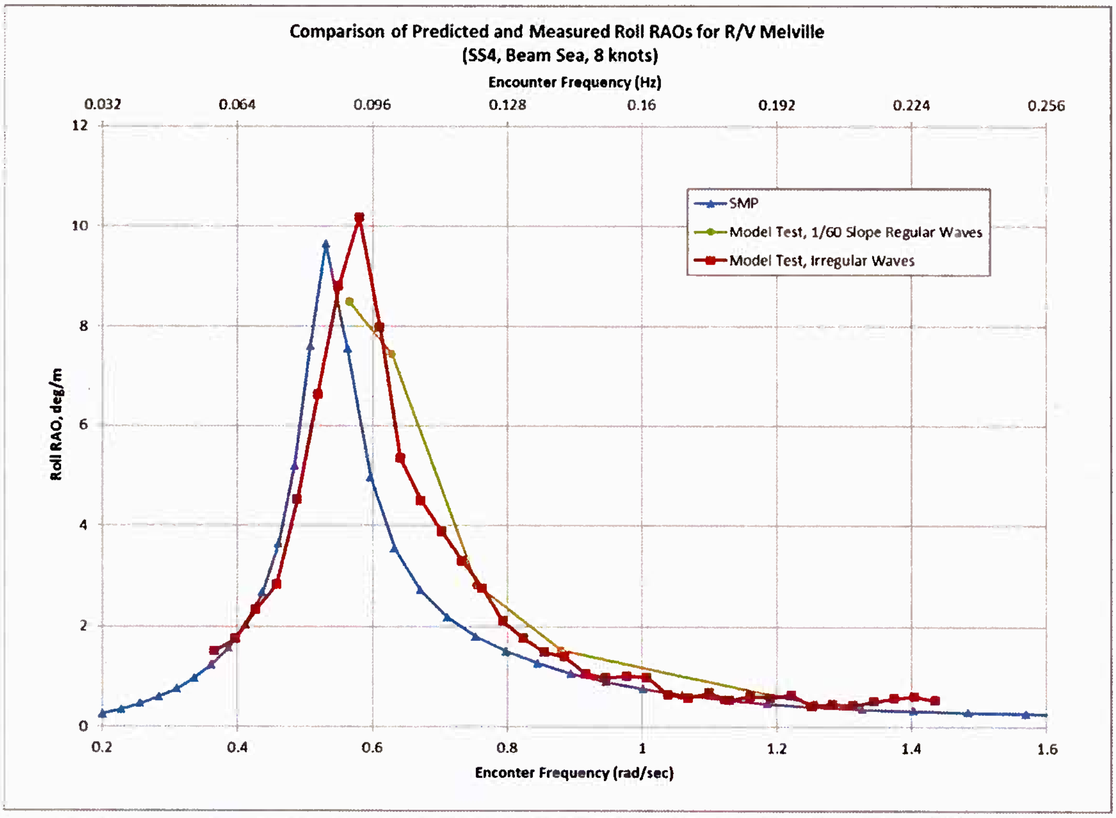

Figure 17. Comparison of Predicted and Measured Roll RAOs (SS4, Beam Sea, 8 knots)

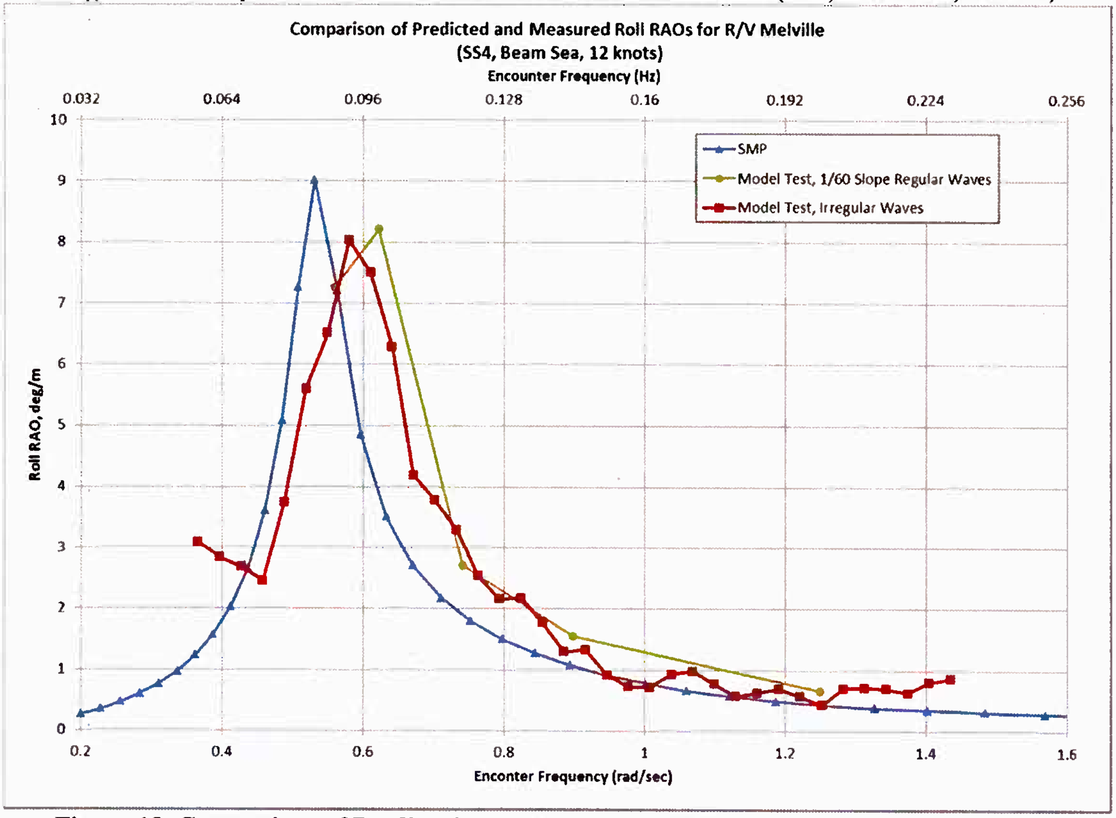

Figure 18. Comparison of Predicted and Measured Roll RAOs (SS4, Beam Sea, 12 knots)

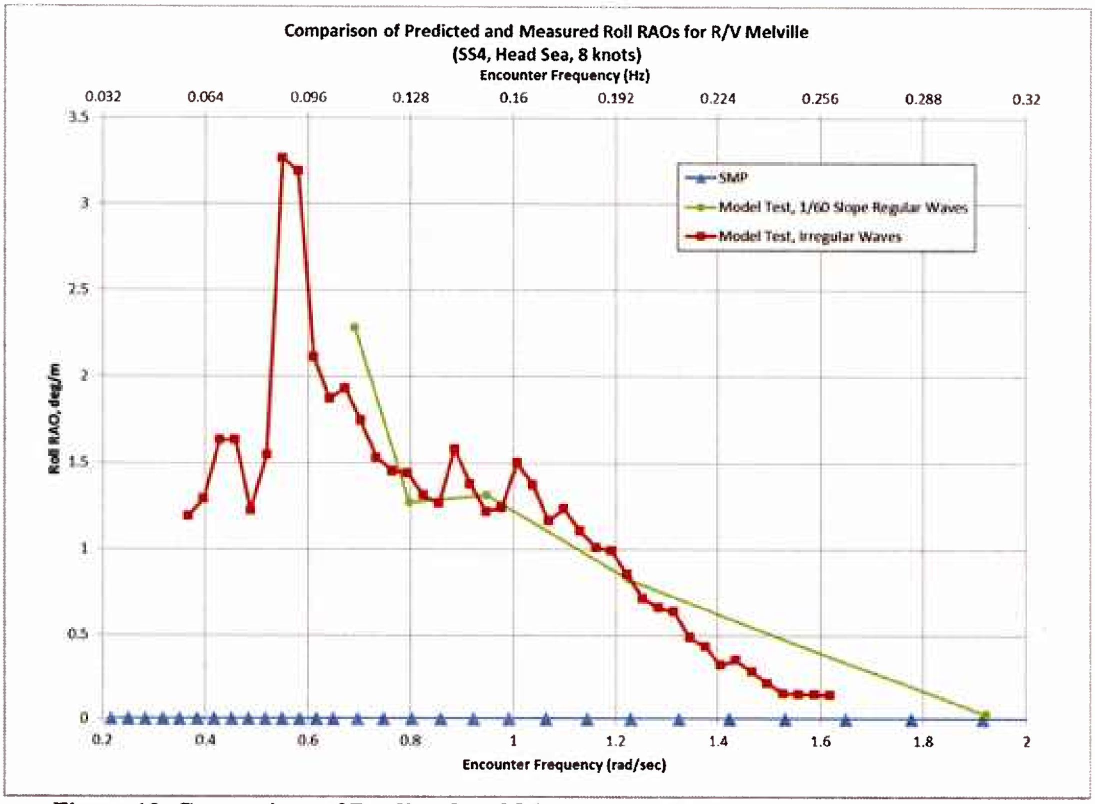

Figure 19. Comparison of Predicted and Measured Roll RAOs (SS4, Head Sea, 8 knots)

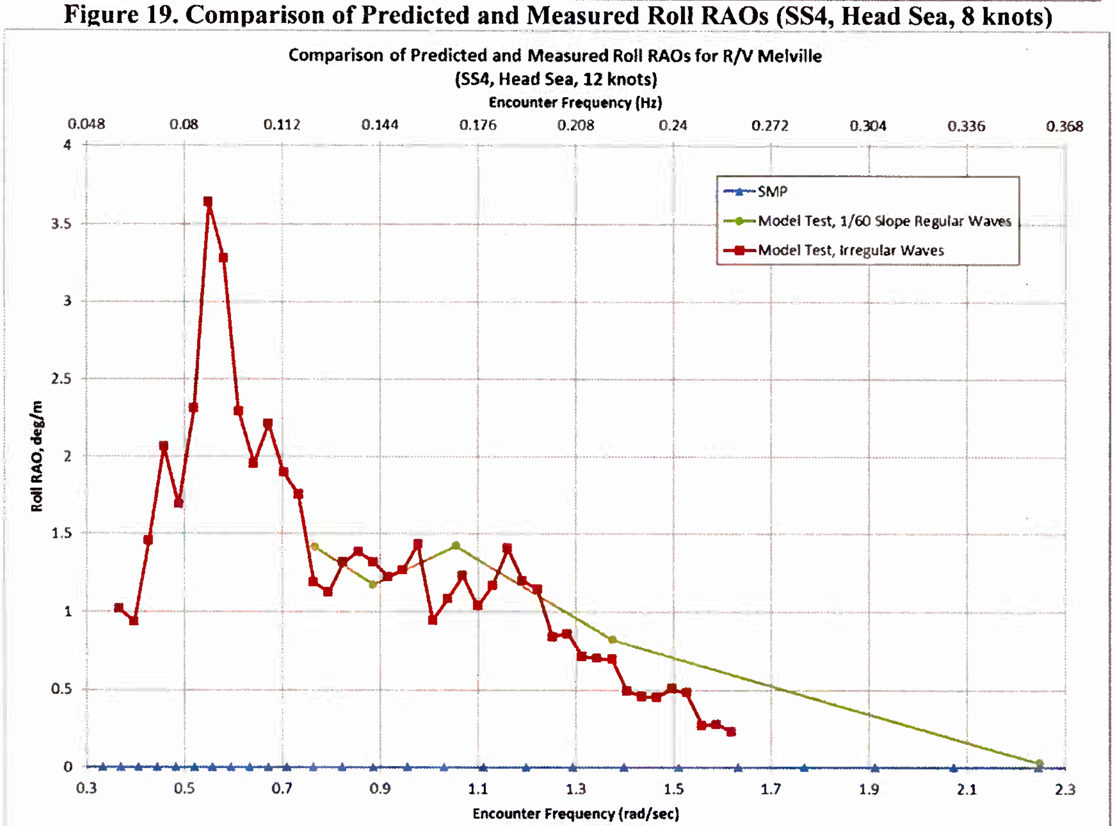

Figure 20. Comparison of Predicted and Measured Roll RAOs (SS4, Head Sea, 12 knots)

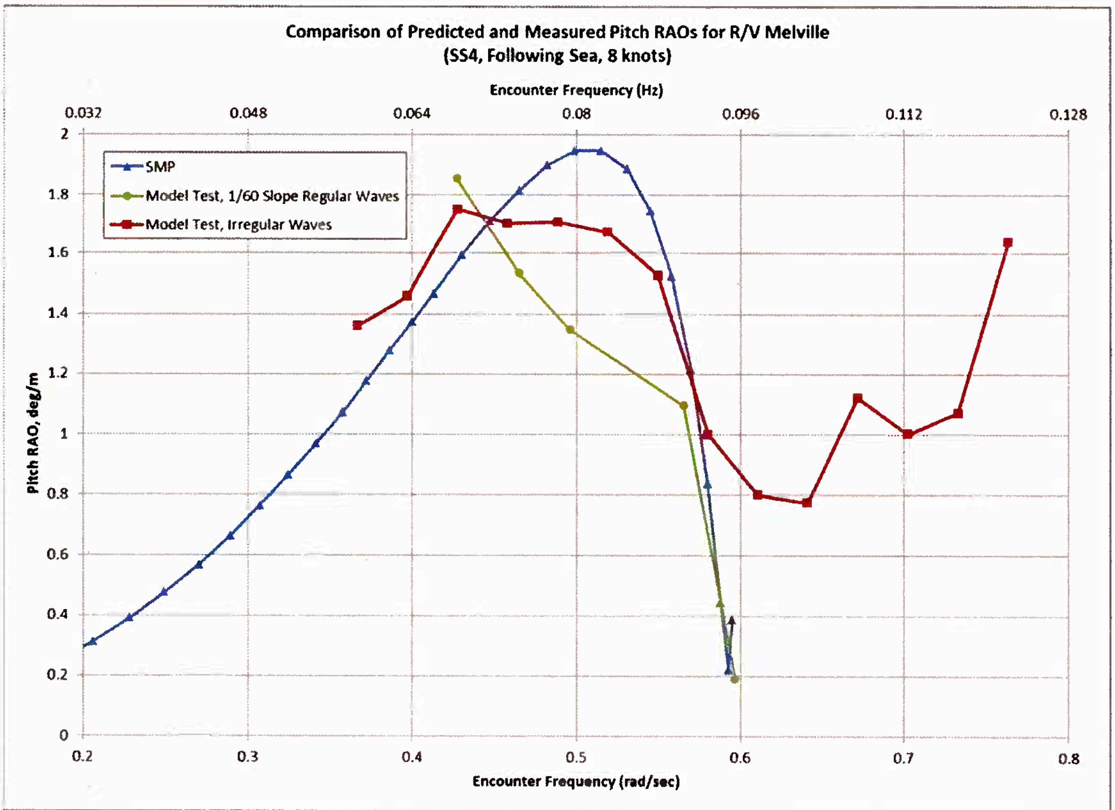

Figure 21. Comparison of Predicted and Measured Pitch RAOs (SS4, Following Sea, 8 knots)

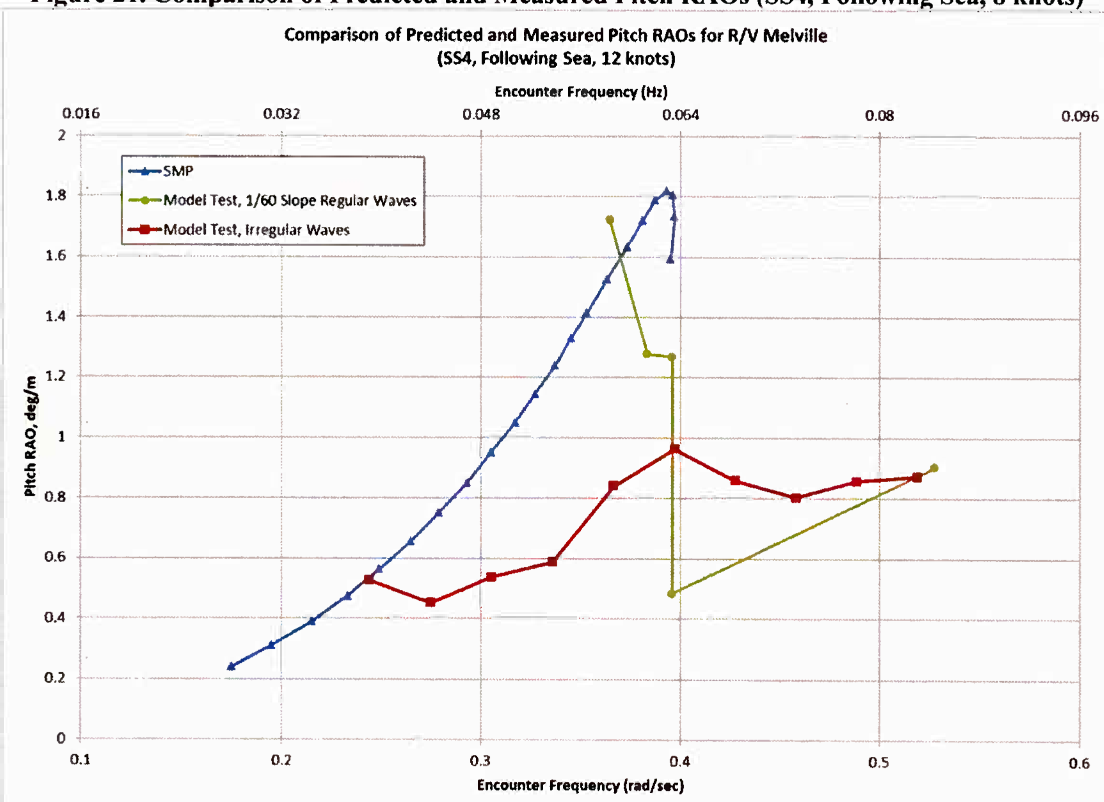

Figure 22. Comparison of Predicted and Measured Pitch RAOs (SS4, Following Sea, 12 knots)

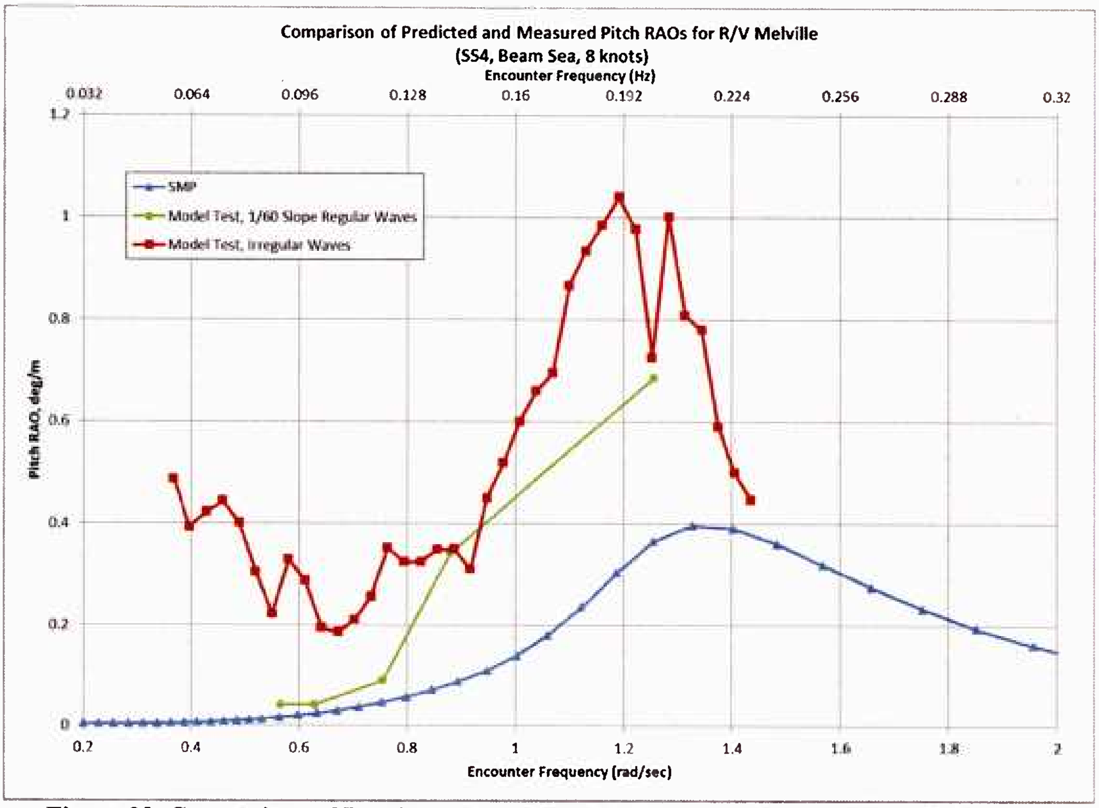

Figure 23. Comparison of Predicted and Measured Pitch RAOs (SS4, Beam Sea, 8 knots)

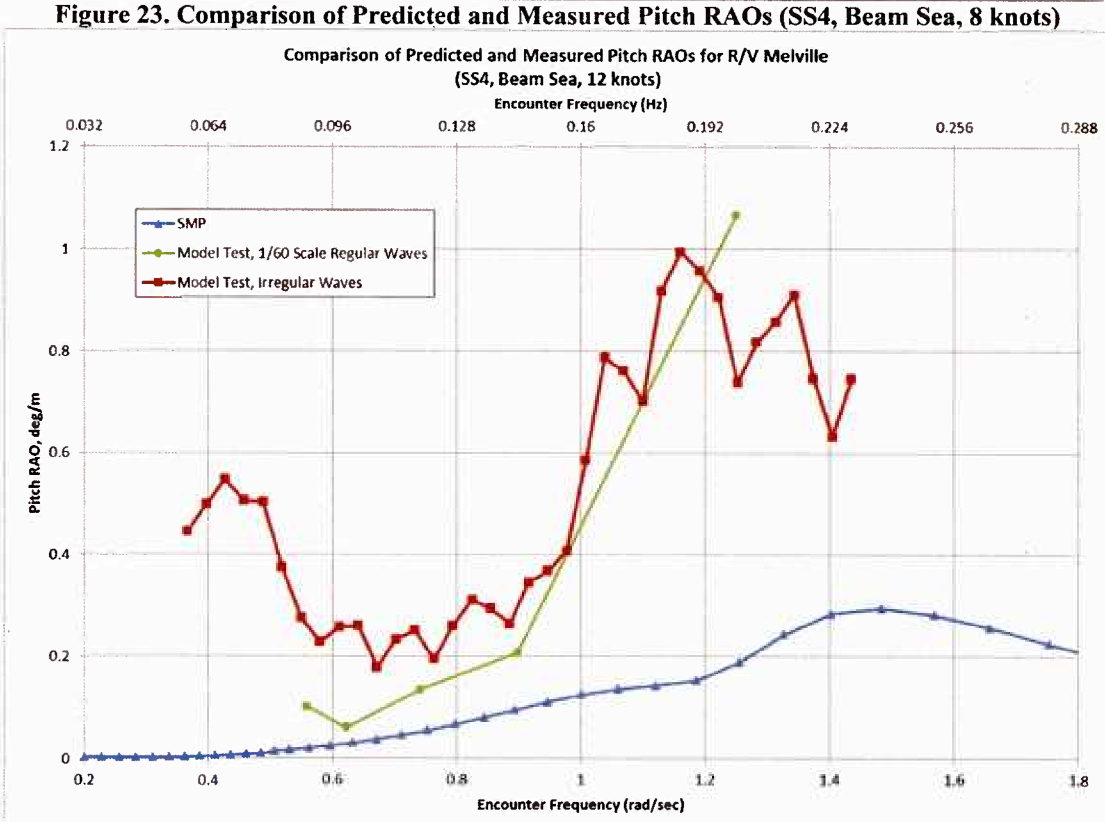

Figure 24. Comparison of Predicted and Measured Pitch RAOs (SS4, Beam Sea, 12 knots)

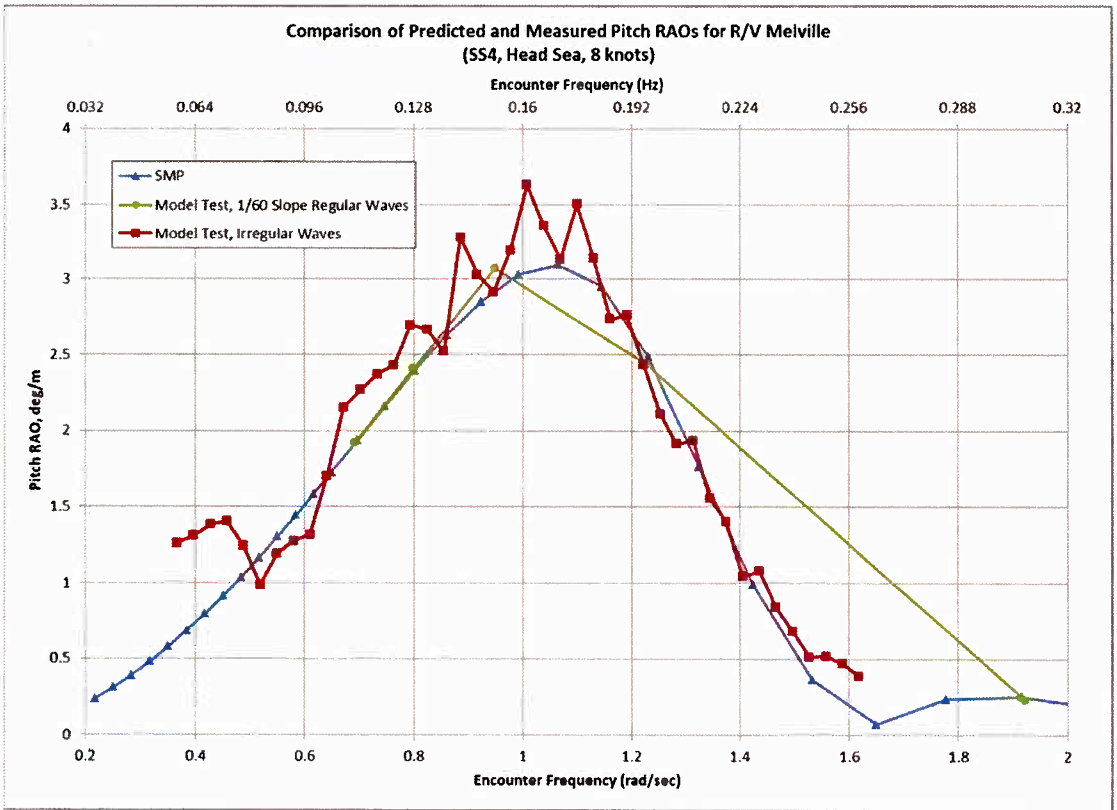

Figure 25. Comparison of Predicted and Measured Pitch RAOs (SS4, Head Sea, 8 knots)

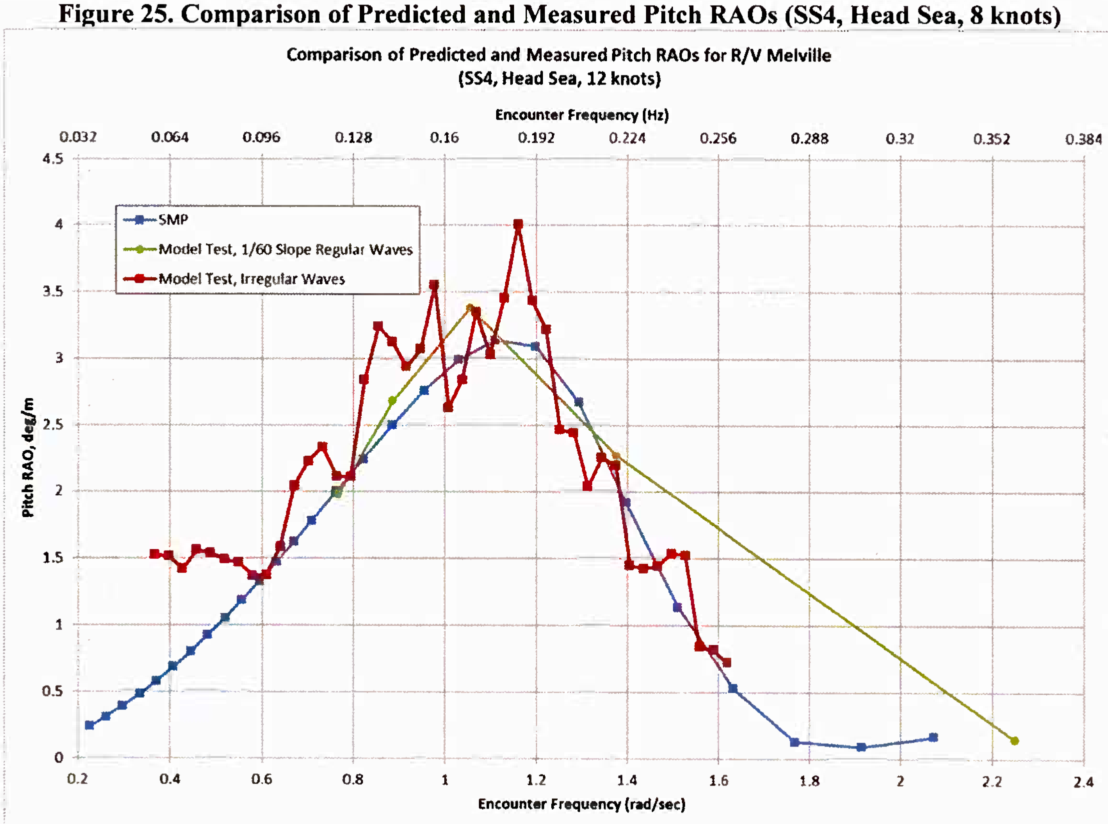

Figure 26. Comparison of Predicted and Measured Pitch RAOs (SS4, Head Sea, 12 knots)

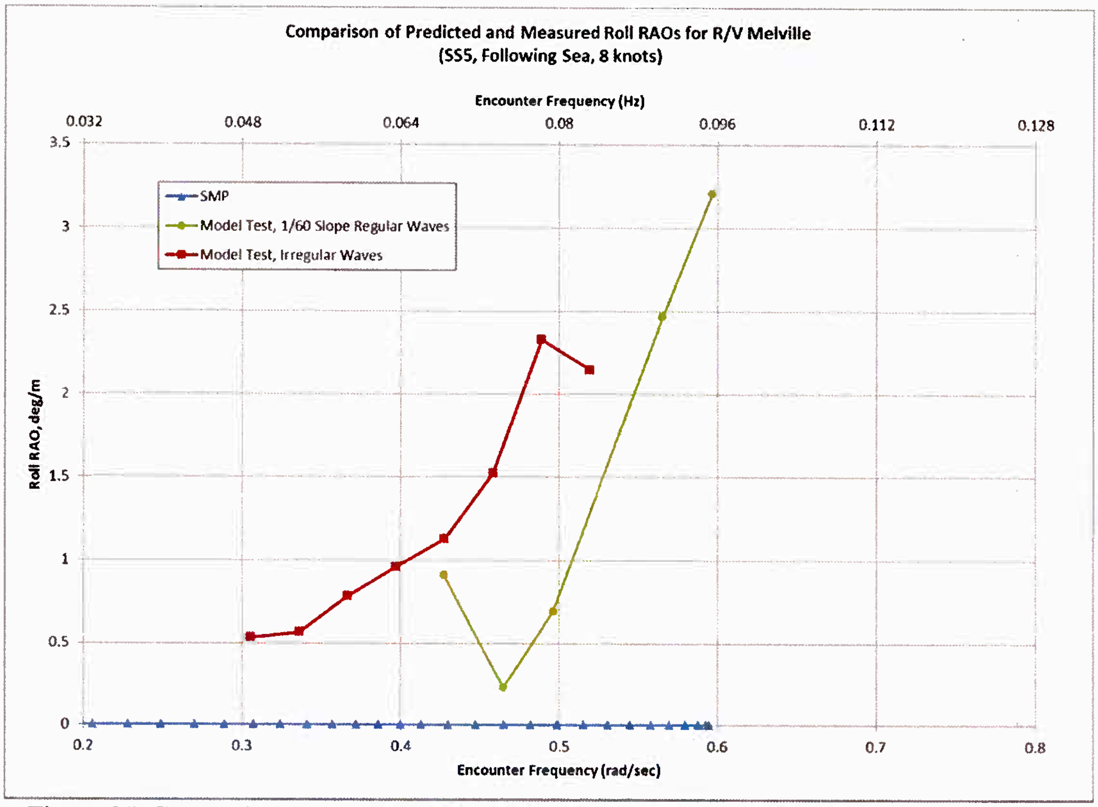

Figure 27. Comparison of Predicted and Measured Roll RAOs (SS5, Following Sea, 8 knots)

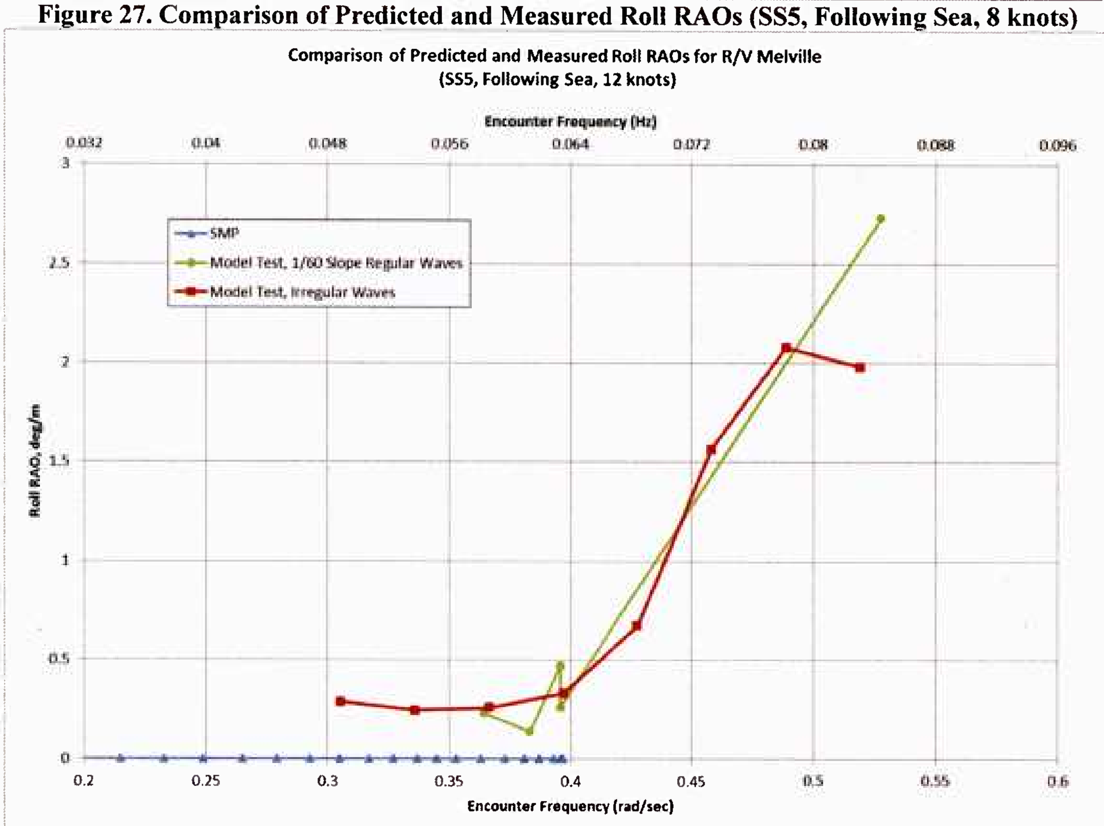

Figure 28. Comparison of Predicted and Measured Roll RAOs (SS5, Following Sea, 12 knots)

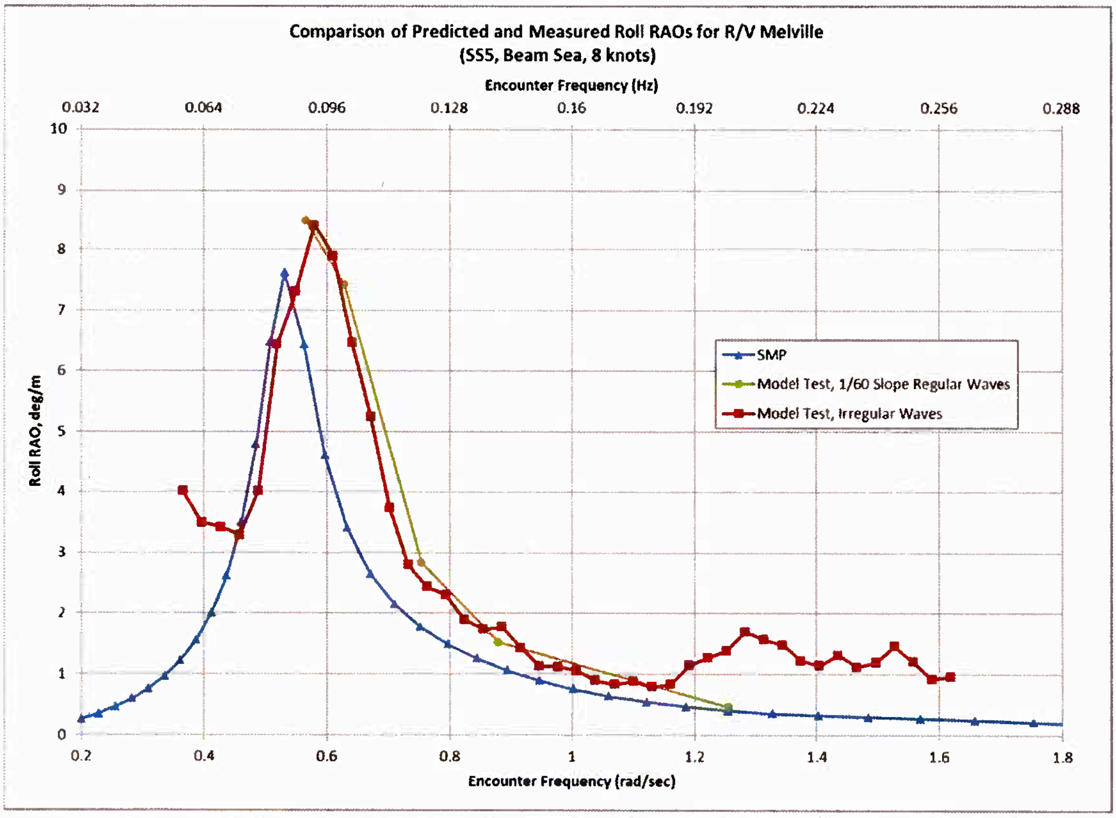

Figure 29. Comparison of Predicted and Measured Roll RAOs (SS5, Beam Sea, 8 knots)

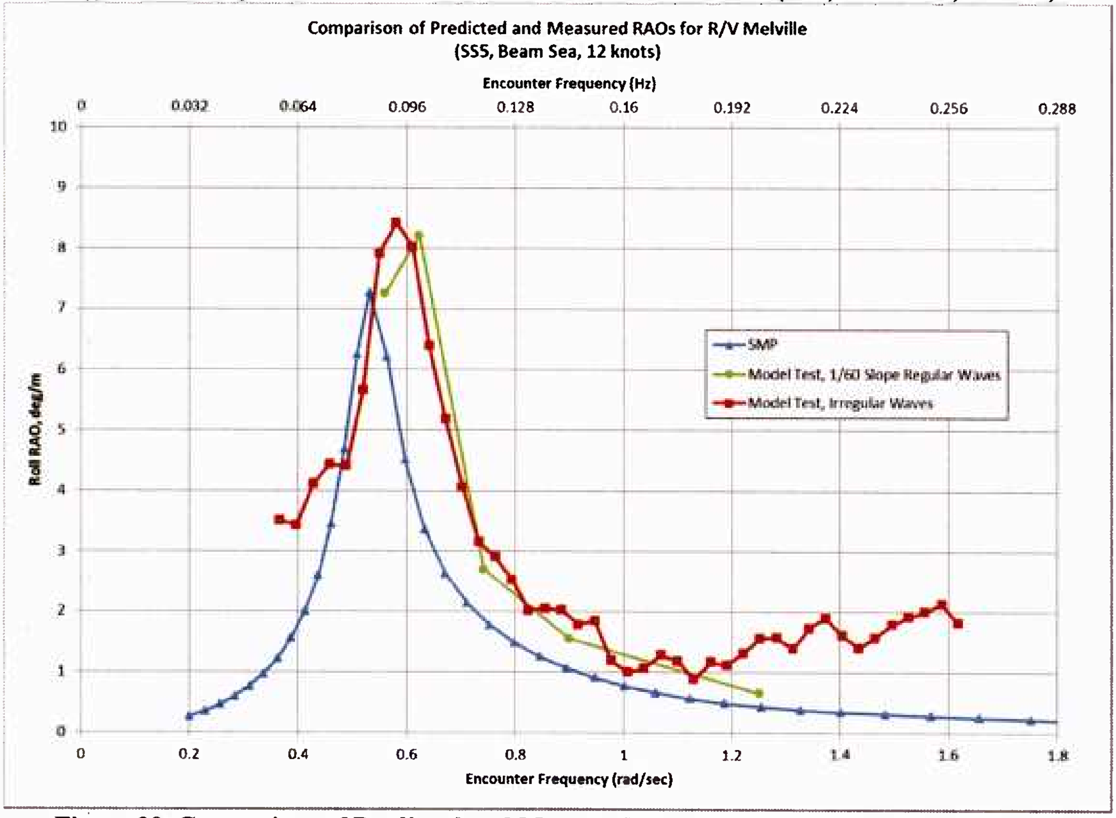

Figure 30. Comparison of Predicted and Measured Roll RAOs (SS5, Beam Sea, 12 knots)

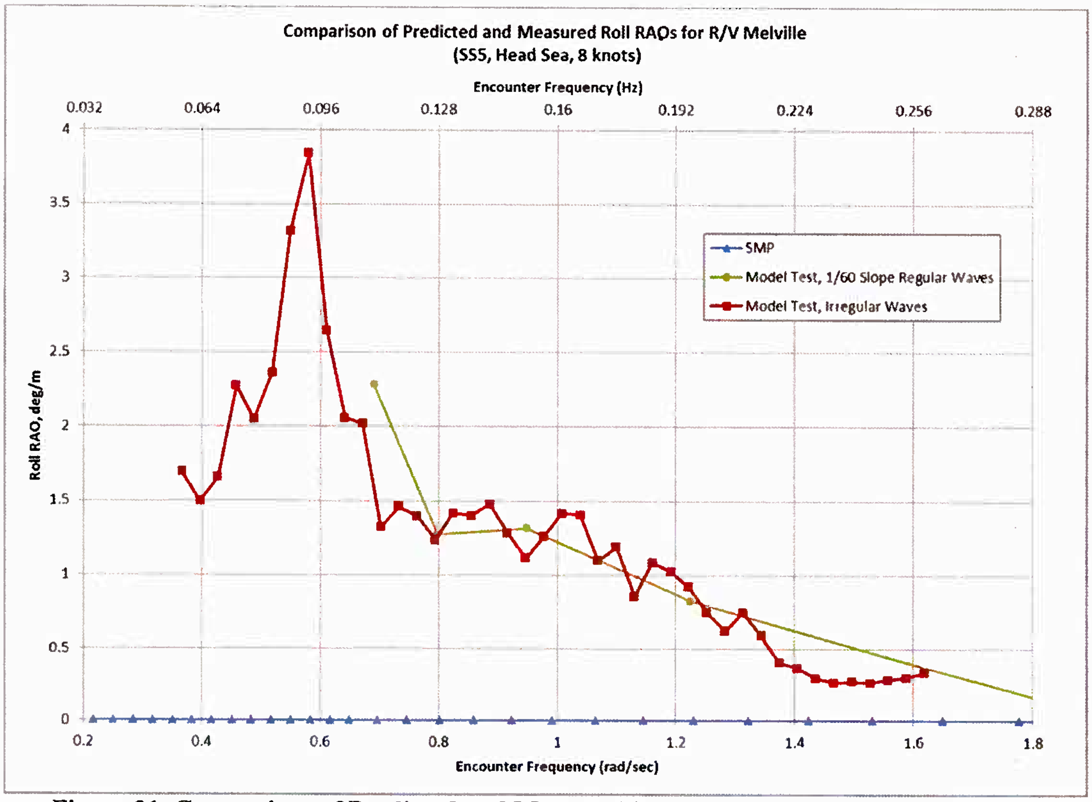

Figure 31. Comparison of Predicted and Measured Roll RAOs (SS5, Head Sea, 8 knots)

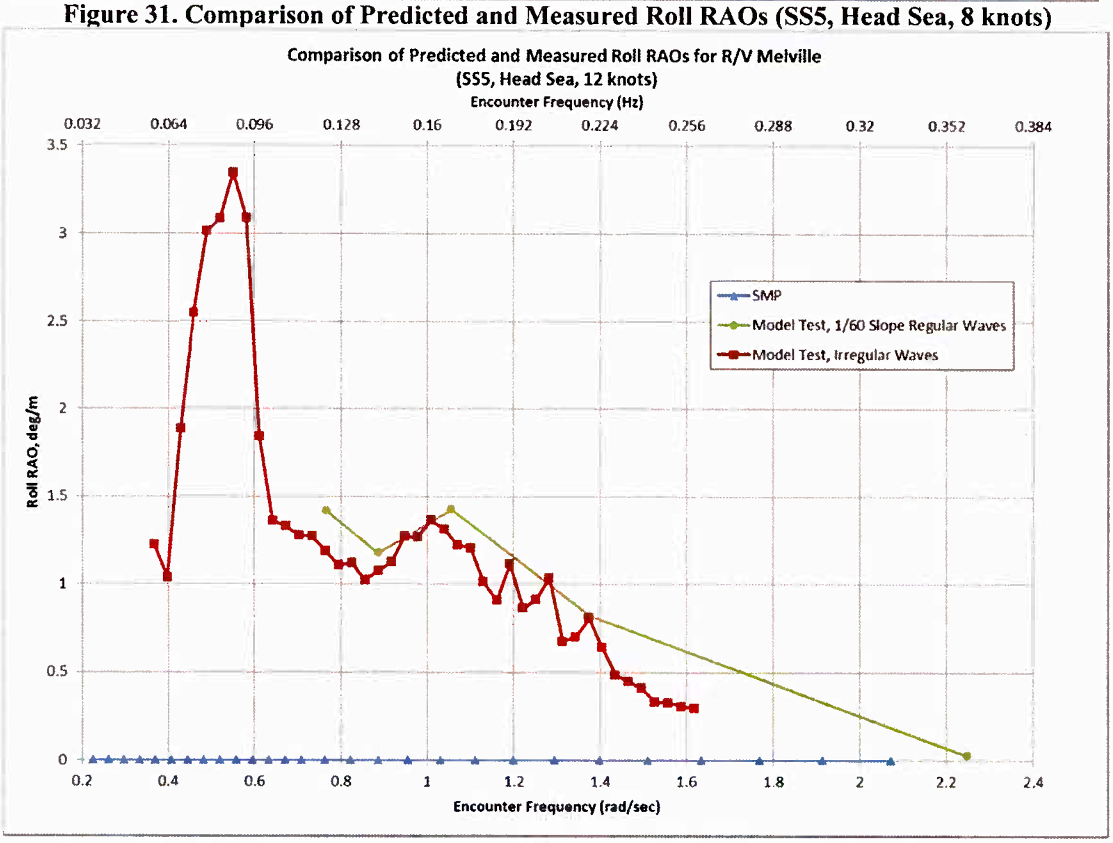

Figure 32. Comparison of Predicted and Measured Roll RAOs (SS5, Head Sea, 12 knots)

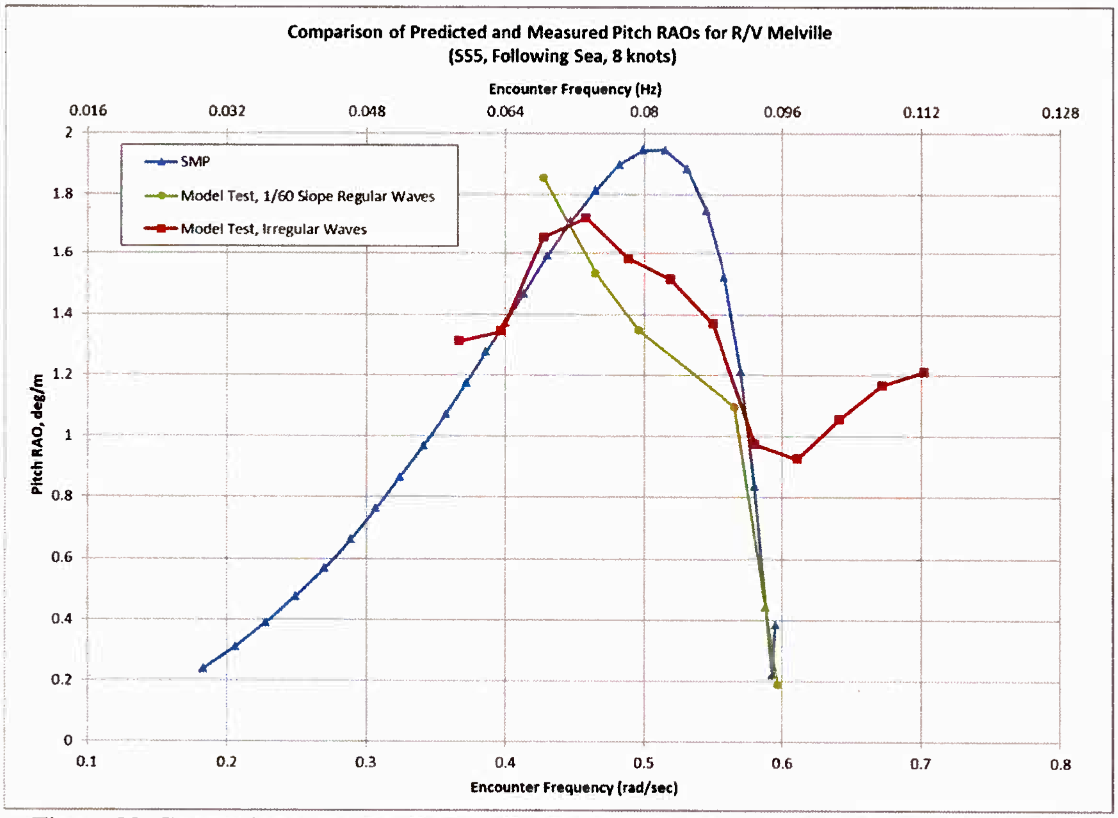

Figure 33. Comparison of Predicted and Measured Pitch RAOs (SS5, Following Sea, 8 knots)

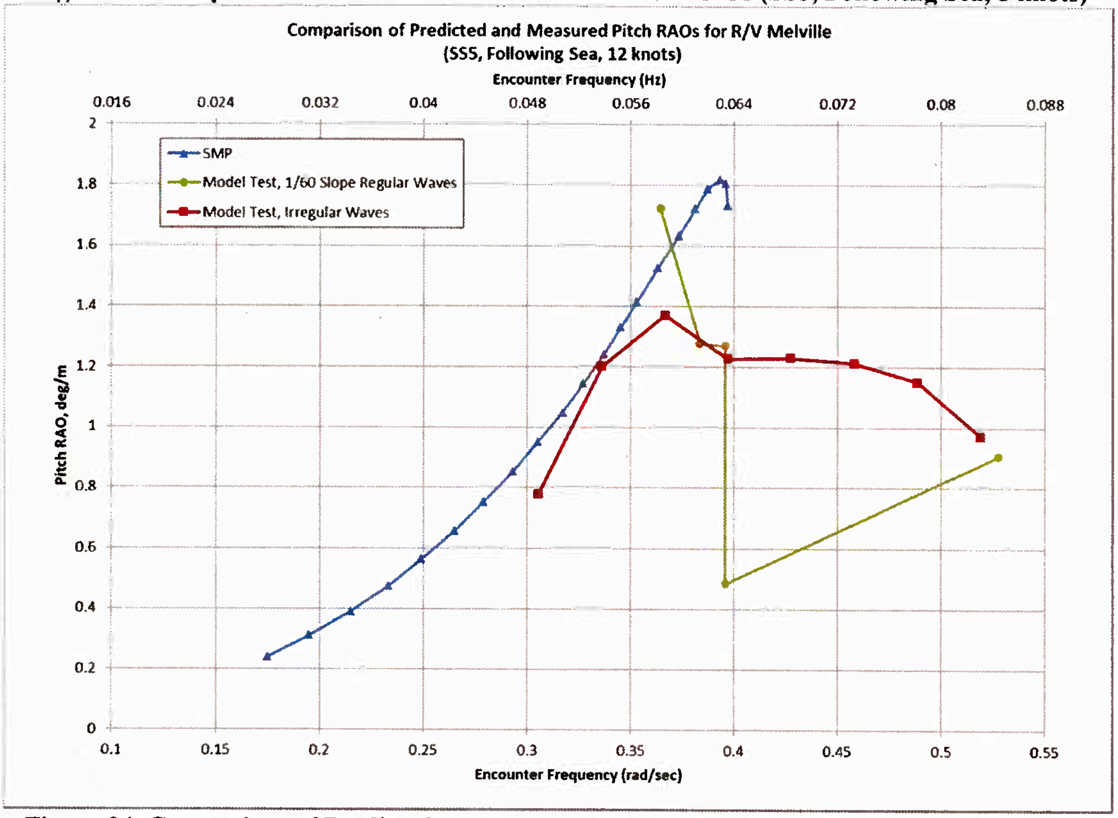

Figure 34. Comparison of Predicted and Measured Pitch RAOs (SS5, Following Sea, 12 knots)

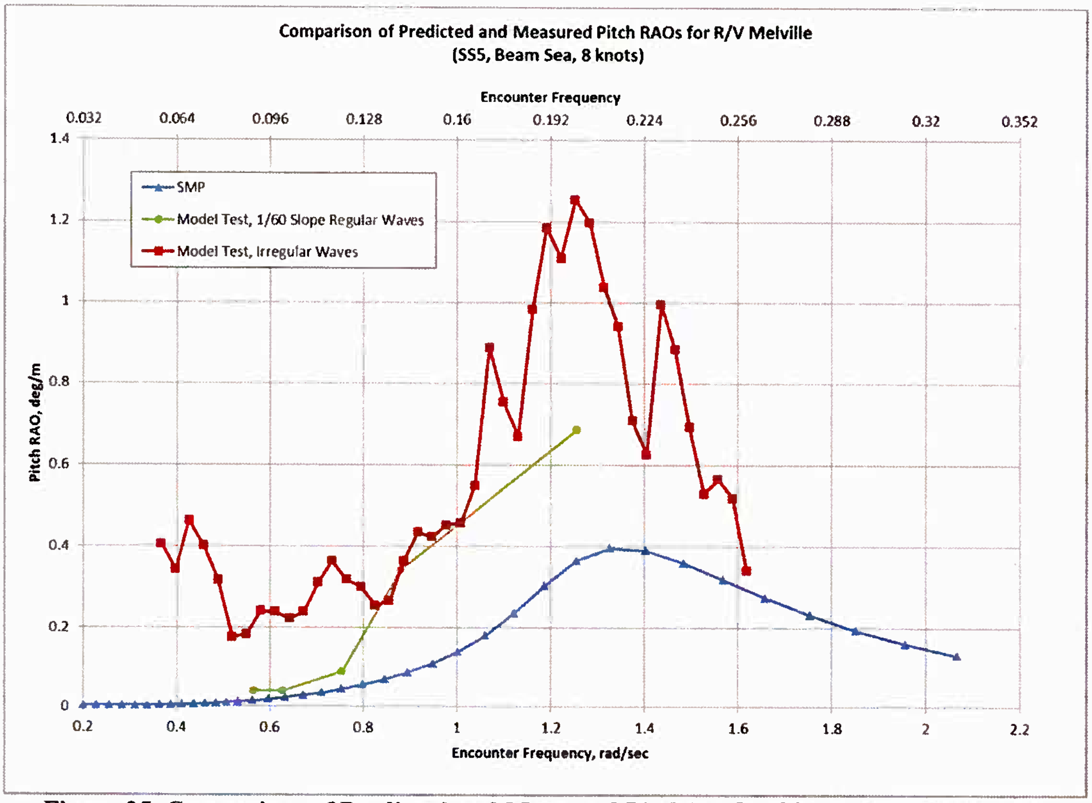

Figure 35. Comparison of Predicted and Measured Pitch RAOs (SS5, Beam Sea, 8 knots)

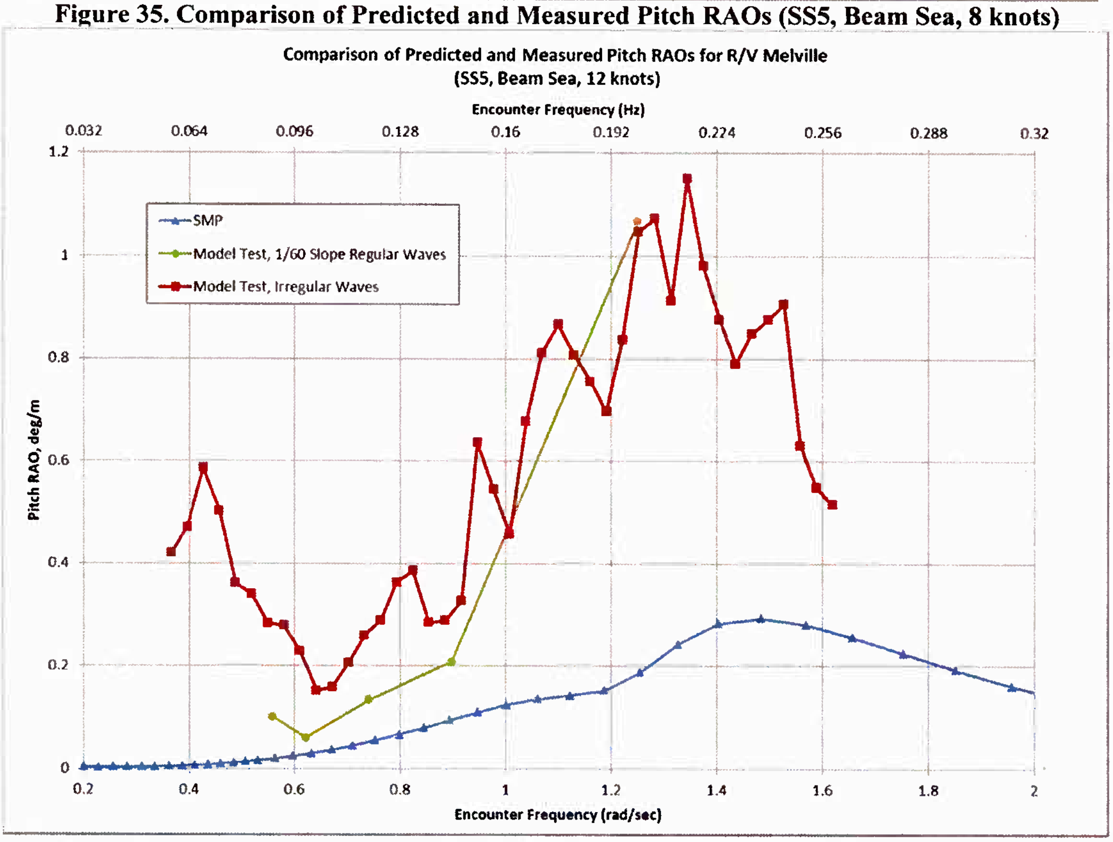

Figure 36. Comparison of Predicted and Measured Pitch RAOs (SS5, Beam Sea, 12 knots)

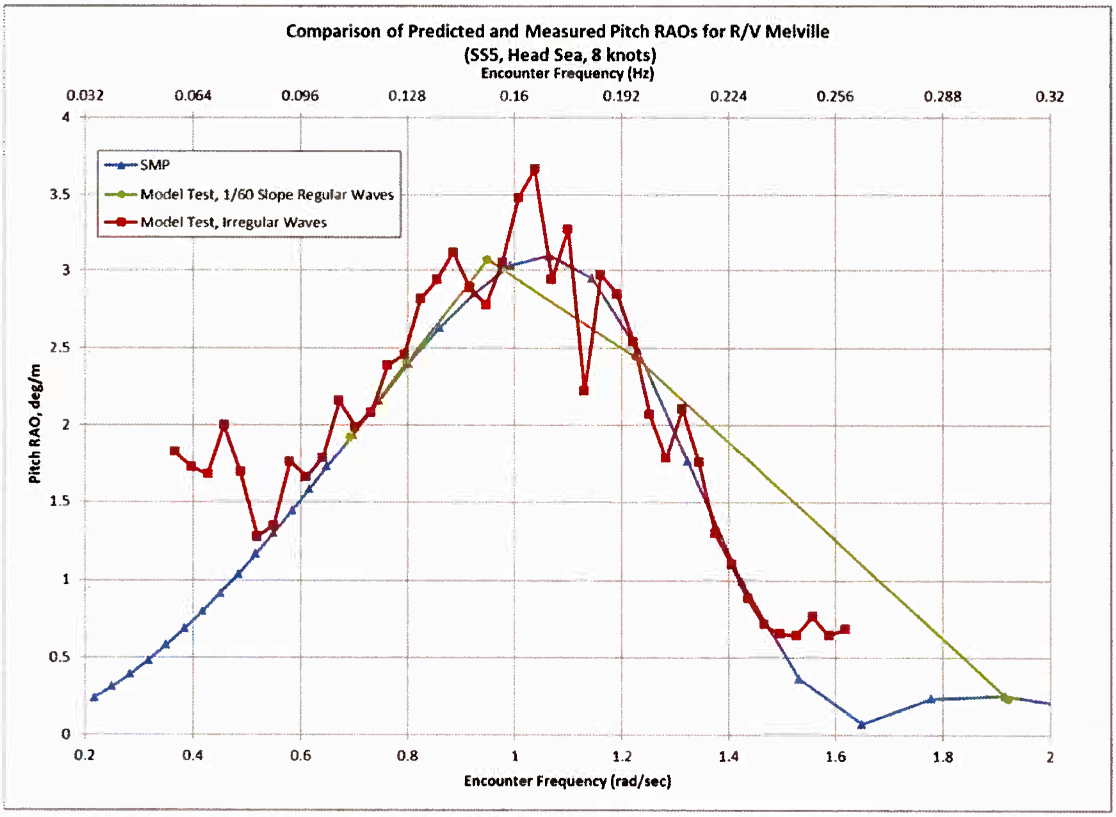

Figure 37. Comparison of Predicted and Measured Pitch RAOs (SS5, Head Sea, 8 knots)

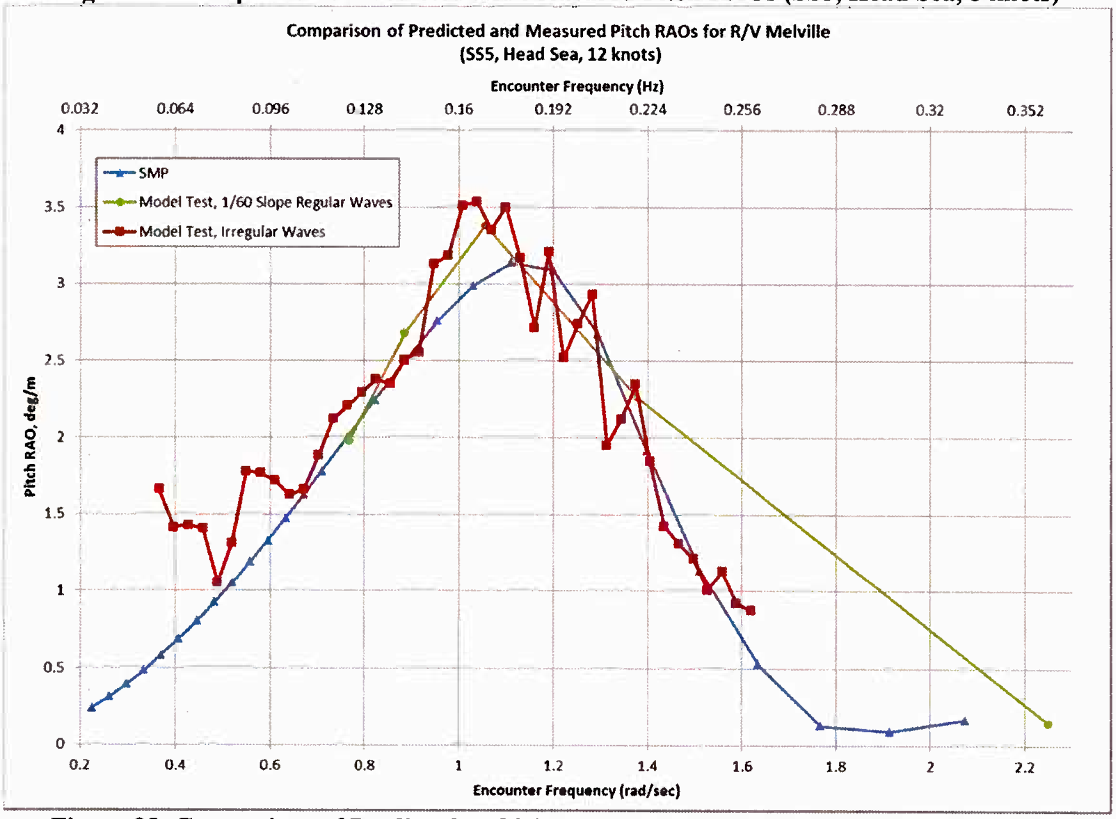

Figure 38. Comparison of Predicted and Measured Pitch RAOs (SS5, Head Sea, 12 knots)

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